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DEFINITION OF MUTUALLY OPTIMUM NDI
AND PROOF TEST CRITERIA FOR
2219 ALUMINUM PRESSURE VESSELS

VOLUME I METHODS

by Fred R. Schwartzberg, Richard G. King, and
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MARTIN MARIETTA CORPORATION

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16. Abstract This program has provided data that help to develop a better understanding of the requirements for proof testing and NDI of aluminum pressure vessels. The following conclusions were drawn: 1. lack-of-fusion weld defects are sufficiently tight in the as-welded condition to be considered undetectable; 2. proof-level loads are required to fully open lack-of-fusion weld defects; 3. significant crack opening occurs at subproof levels so that an inspection enhancement loading treatment designed to avoid catastrophic failure is feasible; 4. currently used proof levels for 2219 pressure vessels are adequate for postproof inspection; 5. quantification of defect size and location using collimated ultrasonic pitch-catch techniques appears sufficiently feasible for tankage to warrant developmental work; 6. for short-time single-cycle pressure-vessel applications, postproof inspection is desirable; 7. for long-term multiple-cycle pressure-vessel applications, postproof inspection is essential for life assurance.					
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FOREWORD

This report describes the results of the first phase of a program to study methods for combined use of nondestructive inspection (NDI) techniques and proof-test logic. This part of the program dealt with development of the concepts and methods. The second phase of the program used a NDI flaw mapping method described in this document to study certain aspects of crack-extension and fracture behavior. A third phase was intended to demonstrate possible application to hardware.

The work was performed under the management of NASA Project Manager Gordon T. Smith.

The Martin Marietta Program Manager for the activity was Fred R. Schwartzberg. Paul M. Lorenz served as Technical Director for the effort described in this document. Assisting Mr. Lorenz in the performance of this work were Messrs. Richard G. King, Paul H. Todd, Jr., and Charles Toth, Jr.

For the benefit of technical readers, raw data and reductions of original engineering drawings are included in the figures.

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SUMMARY

This experimental investigation was undertaken to provide a rational basis for selection of proof-test and nondestructive inspection (NDI) acceptance criteria for 2219 aluminum weldments. Because proof test alone cannot assure integrity for tough materials, NDI must be used as a companion for hardware qualification. A lack-of-fusion defect is particularly difficult to detect and characterize in the as-welded condition. Therefore, proof testing must be used to ensure detectability of this type of defect.

Simulation of crack closure conditions that affect NDI detectability by compressing two blocks showed that forces well above the yield level were required to completely obscure the interface at ambient and elevated temperatures.

Development of techniques for preparation of specimens containing artificially introduced lack-of-fusion weld defects was a significant accomplishment.

As-produced defects were invisible to radiographic inspection and virtually indistinguishable using ultrasonic inspection. The force required to provide full opening of the defects was related to the tightness of the crack.

A method that combined a collimated ultrasonic beam and a pitch-catch technique was used to study the behavior of lack-of-fusion defects in flat welded panels.

This program has provided data that help to develop a better understanding of the requirements for proof testing and NDI of aluminum pressure vessels. The following conclusions were drawn:

- 1) lack-of-fusion weld defects are sufficiently tight in the as-welded condition to be considered undetectable;
- 2) proof-level loads are required to fully open lack-of-fusion weld defects;
- 3) significant crack opening occurs at subproof levels so that an inspection enhancement loading treatment designed to avoid catastrophic failure is feasible;
- 4) currently used proof levels for 2219 pressure vessels are adequate for postproof inspection;
- 5) quantification of defect size and location using collimated ultrasonic pitch-catch techniques appears sufficiently feasible for tankage to warrant developmental work;
- 6) for short-time single-cycle pressure-vessel applications, postproof inspection is desirable;
- 7) for long-term multiple-cycle pressure-vessel applications, postproof inspection is essential for life assurance.

INTRODUCTION

Applicability of linear elastic fracture mechanics theory is limited to the materials in which plastic deformation at the tip of a sharp crack is relatively small and fracture occurs at stress levels less than the material's yield strength. Problems with premature failures have been solved by applying basic principles of fracture mechanics resulting in use of tougher materials, elimination of stress concentrations, and lowering of operating stress levels. The state of the art has progressed to the point where effective prevention of premature failures in pressure vessels can be achieved by judicious selection of proof tests.

The use of both proof-test and nondestructive inspection (NDI) procedures to verify the structural integrity of high-performance pressure vessels is well established. Both procedures are used to identify individual vessels having defects that are large enough to cause operational failures. In the case of vessels fabricated from materials that are relatively brittle under the conditions imposed by the proof test, it is possible to establish a subsequent operational life that is assured by the proof test. This assured operational life is determined from crack-growth projections at the design operational condition of the largest crack that could survive proof-test conditions. Quantification of the most severe initial crack is the essential requirement in the process. For materials that are relatively tough under proof-test conditions (such as 2219 aluminum weldments), the proof test alone is not sufficient to quantify a maximum survivable crack size. Under such conditions, both proof testing and NDI techniques are needed to provide assurance of any specific operational life. This program examined the effectiveness of NDI in identifying and quantifying buried weld defects and the enhancement of flaw detectability that can be obtained by inspection during and after loading.

The program's specific objective was to provide a basis for selection of proof-test and NDI acceptance criteria for 2219 aluminum weldments. The approach recognized that assurance of structural integrity by proof test alone might not be feasible for materials exhibiting high fracture toughness. For such conditions, NDI employed in conjunction with the proof test may be used to detect flaws that can not be effectively screened by either NDI or proof test alone. The experimental approach was designed to provide data on idealized (very tight) and actual crack closure conditions, preload levels required for enhancement of crack detectability, and crack growth characteristics of embedded and surface lack-of-fusion defects. In conjunction with the needs of this program, a technique was developed for flaw mapping fully embedded defects and used to measure crack growth in welded specimens.

This report describes the results of the first part of a three-part program. The efforts described in this report are:

- 1) Characterization of material properties;
- 2) Crack closure conditions required to obscure lack-of-fusion defects (LFD);
- 3) Development of LFD test specimens;
- 4) Effect of loading conditions on NDI system response to lack-of-fusion defects;
- 5) Postload cyclic crack-growth characteristics;
- 6) Definition of proof-test criteria.

Two additional efforts were undertaken to use the ultrasonic flaw mapping technique to:

- 1) Study several fracture behavior parameters such as crack-opening displacement (COD) gage correction factors, crack closure conditions, and flaw extension characteristics;
- 2) Determine applicability to hardware evaluation, particularly railroad rails.

This additional work is reported in Volumes II and III.

CHARACTERIZATION OF PARENT- AND WELD-METAL PROPERTIES

Two gages of 2219-T87 aluminum alloy were used in this program. Both parent and welded material of each gage thickness were tensile tested to thoroughly characterize the mechanical properties of the stock used and to assess the welding techniques.

Tensile tests performed on parent-metal coupons of the 10.2-cm (4-in.) and 2.5-cm (1-in.) plate stock revealed that the strength and ductility were in accord with anticipated results for 2219-T87 (table I). The thinner plate exhibited similar properties for the two directions evaluated--indicating satisfactory cross rolling. The heavier plate exhibited less ductility in the long and short transverse directions than in the longitudinal direction.

TABLE I. - TENSILE STRENGTHS* OF PARENT MATERIAL

Stock thickness, cm (in.)	Grain direction	Ultimate strength,		Yield strength (0.2% offset)		Elongation, %	Reduction in area, %
		MN/m ²	(ksi)	MN/m ²	(ksi)		
10.2 (4)	Longitudinal	469	(68.0)	388	(55.3)	11.2	19.1
	Long transverse	460	(66.7)	377	(54.7)	5.7	8.2
	Short transverse	436	(63.3)	374	(54.3)	4.6	5.8
2.54 (1)	Longitudinal	460	(66.7)	373	(54.1)	12.0	20.2
	Long transverse	460	(66.7)	375	(54.4)	12.3	28.1

* 8-mm (5/16-in.) diameter specimens.

The strength of welded material is given in table II. Yield strength and elongation values were comparable for the cylindrical and flat weldments. Flat-weldment ultimate strength was almost 20% lower than that of cylindrical weldments. Data reported are typical for welded 2219-T87.

TABLE II. - TENSILE STRENGTH* OF WELDED MATERIAL

Weld- ment type	Ultimate strength,		Yield strength (0.2% offset)		Elongation in indicated gage length, %	
	MN/m ²	(ksi)	MN/m ²	(ksi)	1.27 cm (0.5 in.)	2.5 cm (1.0 in.)
Cylindrical	294	(42.6)	143	(20.8)	10.1	7.9
	206	(42.9)	116	(16.9)	18.7	7.0
	307	(44.6)	143	(20.7)	12.3	6.7
	302	(43.8)	148	(21.5)	13.4	6.2
	305	(44.2)	163	(23.6)	11.0	6.1
	300	(43.5)	143	(20.7)	13.7	6.5
	300 avg	(43.6)	143 avg	(20.7)	13.2	6.7
Flat	236	(34.2)	96	(14.0)	14.4	10.1
	254	(36.8)	176	(25.5)	13.2	7.9
	245 avg	(35.5)	136 avg	(19.8)	13.8	9.0
*8-mm (5/16-in.) diameter specimens.						

CRACK CLOSURE CONDITIONS REQUIRED TO OBSCURE LACK-OF-FUSION DEFECTS

A study of the interface forces necessary to obscure lack-of-fusion-type defects from current NDI inspection methods was performed for selected conditions of temperature and surface roughness. Three conditions of roughness and three temperatures were used.

Average surface roughness, (μ in. rms)		Specimen group identification
	17	A
	62	B
	131	C
Temperature,	K	($^{\circ}$ F)
	294	(70)
	422	(300)
	533	(500)

Table III shows actual surface roughness readings for the blanks prepared for this task. Values were measured using a gage and were quite consistent. Specimens for this work consisted of mating blocks with carefully machined surfaces. Figure 1 shows the geometry of the specimen, which contains a truncated conical test section. The original design used a constant-diameter test section, but was discarded when preliminary tests showed that the loads required to obscure the ultrasonic signal at the faying surfaces were greater than the load capacity of the testing machine. The conical geometry concentrated specimen yielding at the contact surfaces and provided improved structural stability. Note the requirement for a flat mating surface flat within 0.10 mm (0.0004 in.) . The specimen contained a recess along the centerline for placement of an ultrasonic transducer, and a flat surface adjacent and parallel to the mating face for placement of an ultrasonic transducer.

To assure uniformity of loading for the compression loading to obscure the interface as well as for tension testing of welded specimens, a specimen grip fixture was designed and fabricated. Figures 2, 3, and 4 show the salient features of the fixture. The main grip component (-001), centering accessory (-011), and loading rod (-007) are shown in figure 2. For compression testing, a spherical seat assembly (-003 and -005) was used (fig. 2). Figure 4 is a drawing of the fixture as assembled for tension and compression. Assembly of the centering device is also shown.

Specimen identification	Roughness, $\mu\text{in. rms}$
A-1	14.3
A-2	19.8
A-3	18.7
A-4	13.2
A-5	19.8
A-6	18.7
A-7	13.2
A-8	19.8
B-1	59.4
B-2	61.6
B-3	64.9
B-4	57.2
B-5	64.9
B-6	64.9
B-7	63.8
B-8	61.6
C-1	132
C-2	132
C-3	132
C-4	132
C-5	123
C-6	132
C-7	132
C-8	132



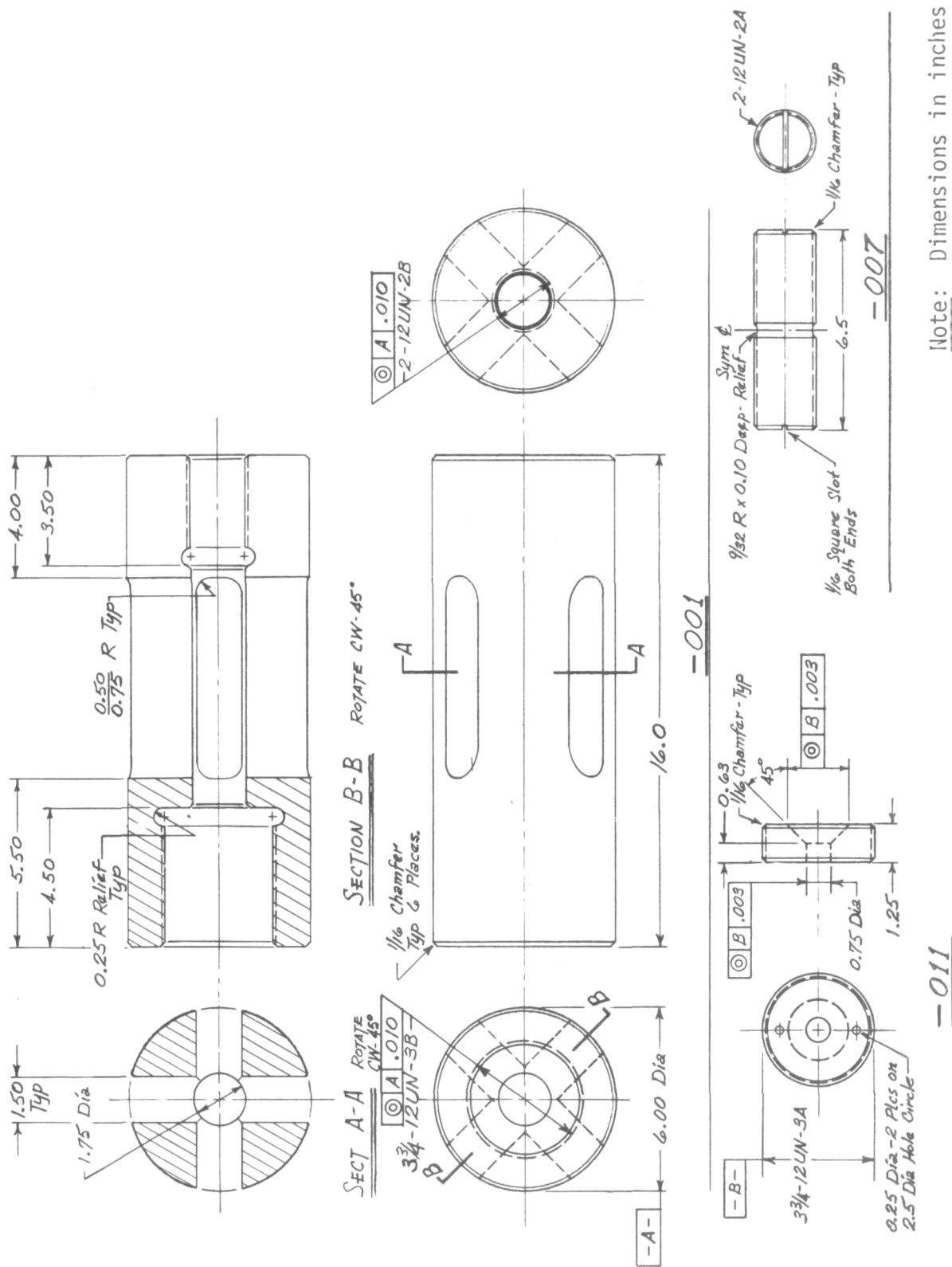
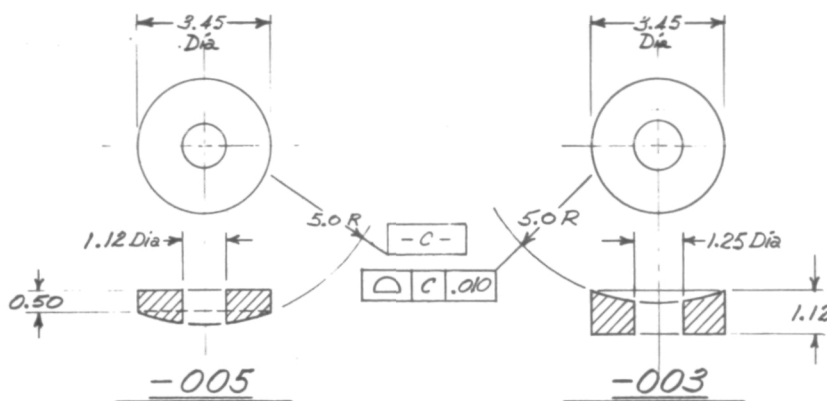
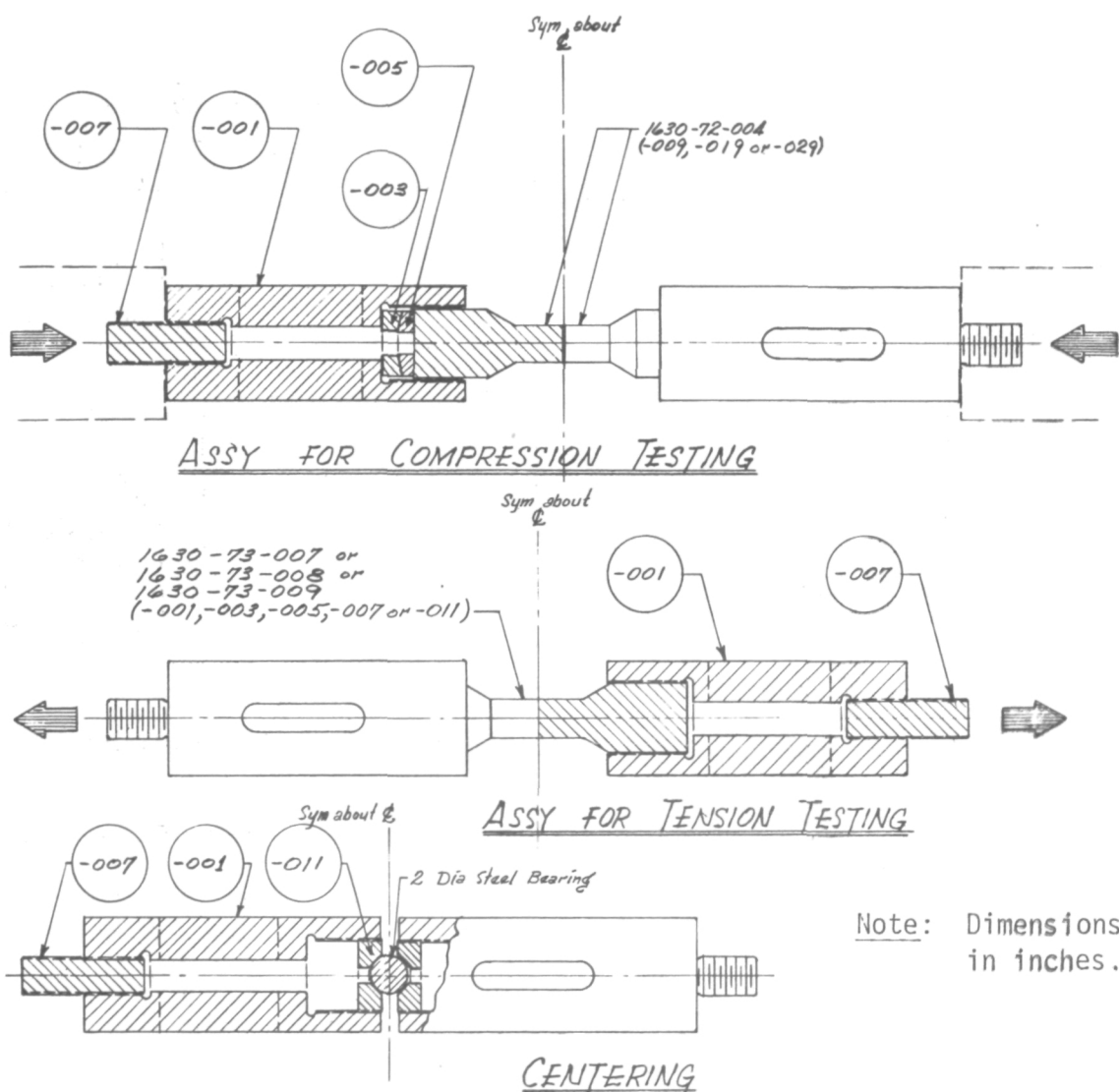


Figure 2. - Components of gripping system.



Note: Dimensions in inches.

Figure 3. - Spherical seat components for compression testing.



Note: Dimensions in inches.

Figure 4. - Assembly schemes for tension and compression testing.

The ultrasonic test setup is shown schematically in figure 5. The equipment consisted of:

- 1) Sperry UM-715 reflectoscope (with 10-N pulser/receiver plug-in unit);
- 2) Arenberg 0-122-dB attenuator;
- 3) Polaroid CR-9 camera;
- 4) Two zirconate titanate ultrasonic transducers, 5-MHz (Automation Industries 57A2623);
- 5) Zirconate titanate ultrasonic transducer, 10-MHz (Automation Industries 57A34631);
- 6) Zirconate titanate ultrasonic transducer with 70° incident angle in aluminum (Automation Industries 57A3087).

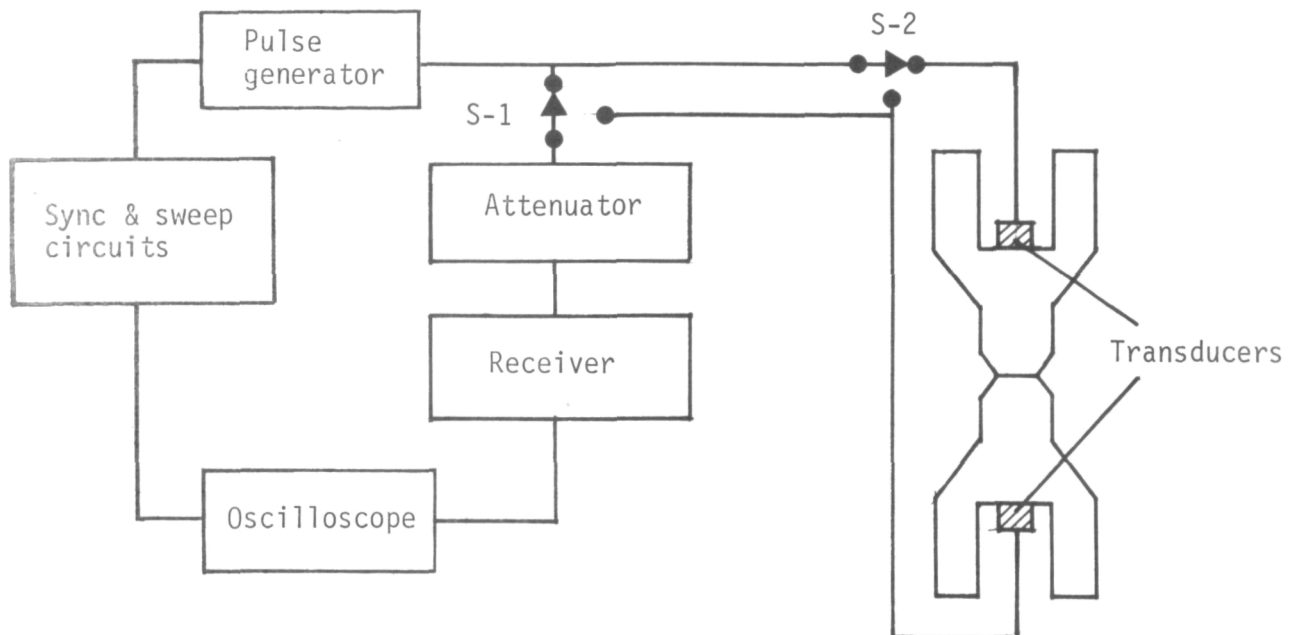


Figure 5. - Schematic of ultrasonic test apparatus.

Each pair of compression-block test specimens for room-temperature testing was centered in the load fixture to bring the faying surfaces in close contact with each other. A small load of about 890 N (200 lb) was applied to the test blocks to prevent a shift (change of respective position) between the two surfaces of the test specimen during transducer alignment. The pulse echo transducer was adjusted until the maximum level of reflected energy was

attained. The shear pulse echo transducers were aligned to give maximum reflected signal, then clamped in place for signal monitoring. As the reflected shear signal failed to respond to the increasing load, and presumably to closing of the faying surfaces, the technique of fixed-position monitoring was modified by shifting the transducer position to locate the maximum reflected signal at each load increment. The number and spacing of load increments were selected to provide accurate definition of the curves (e.g., where the gradients were large, more frequent data points were obtained).

Several trials were run to develop an acceptable degree of proficiency in centering ultrasonic devices, determining the required load levels, and ensuring precise specimen-blank alignment. After the trial runs, additional specimens were subjected to systematic testing to determine the effect of surface roughness and compressive load levels on the strength of the ultrasonic signals and x-ray detection capability.

Compressive specimens C-7 and C-8 were used for preliminary tests at room temperature. Immersion-type transducers were employed for longitudinal pulse-echo and through-transmission techniques using Kenny vacuum oil, Type A, as a couplant. Alignment of these transducers perpendicular to the specimen faying surface was found to be critical. Therefore, several modifications were made to the ultrasonic alignment apparatus. Two ultrasonic frequencies (5 and 10 MHz) were investigated by the pulse-echo technique. The frequencies were chosen because they were not highly attenuated in aluminum, yet provided a wavelength suitable for effective defect resolution. Furthermore, these frequencies are consistent with current production inspection practices.

Figure 6 is a graph of the relative signal strength required to provide a constant-amplitude ultrasonic signal on the oscilloscope versus compressive load on the specimens for two longitudinal-wave pulse-echo transducers. This test was performed with specimens C-7 and C-8 after they had been cold worked by plastic deformation during a previous test. However, the surfaces had been remachined before the tests.

Figure 7 is a graph of signal strength versus compressive load for specimens A-3 and A-4 with ground surfaces, comparing the pulse-echo method with the shear-wave method. While the specimen exhibited plastic deformation, none of the ultrasonic signals were completely lost during the test. Because of a higher signal-strength level in the preliminary tests, a 5-MHz transducer was selected for pulse-echo tests.

Room-temperature test results are presented in figures 8, 9 and 10. Pulse-echo (longitudinal wave) and through-transmission techniques were used for all three tests. The shear (pulse-echo) technique was used for the coarser two finishes.

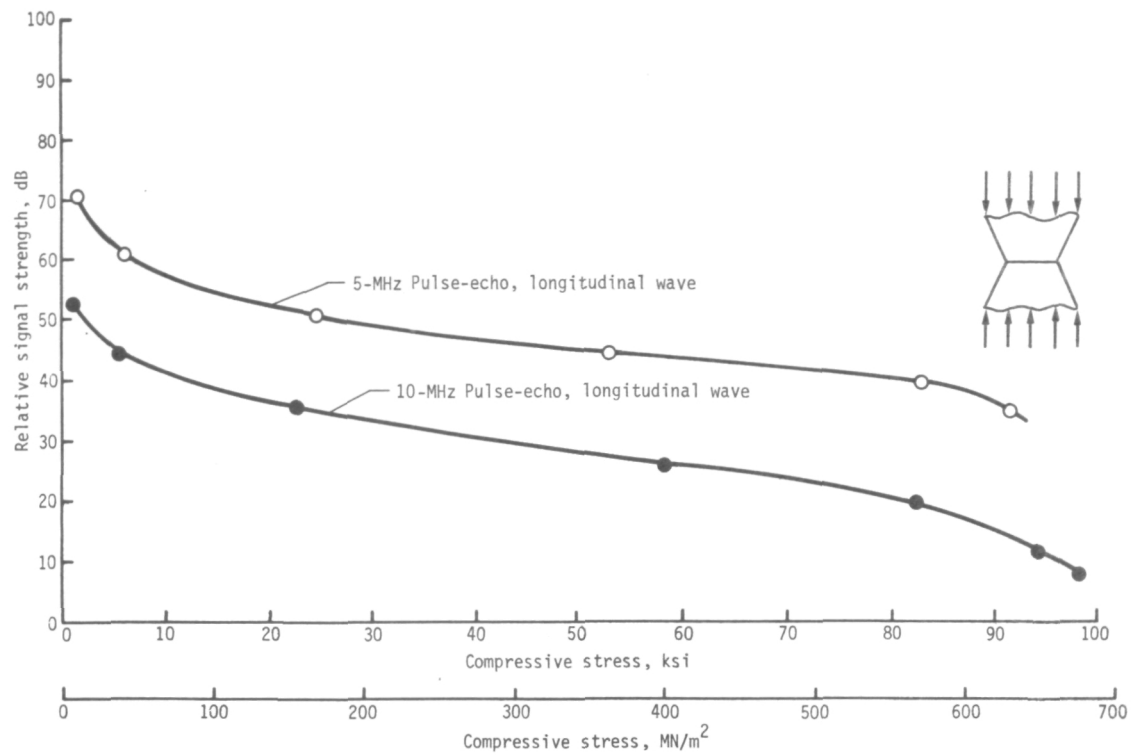


Figure 6. - Effect of pulse-echo frequency on compressive stress vs ultrasonic signal strength.

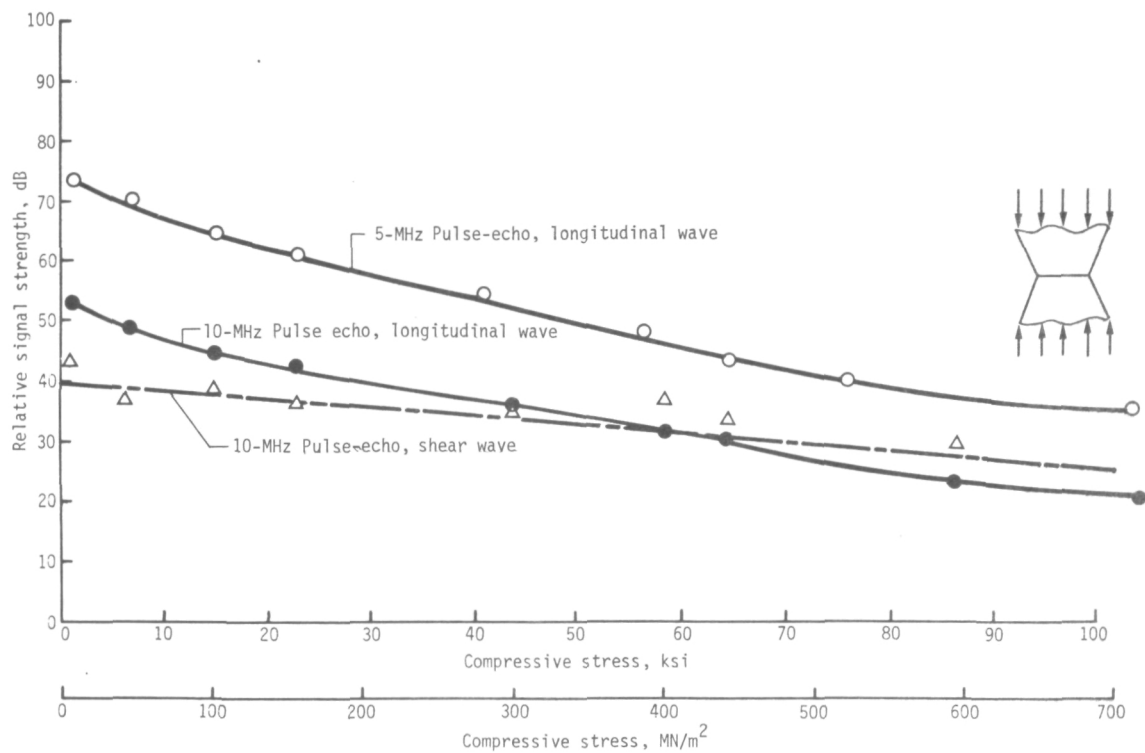


Figure 7. - Effect of ultrasonic method on compressive stress vs ultrasonic signal strength.

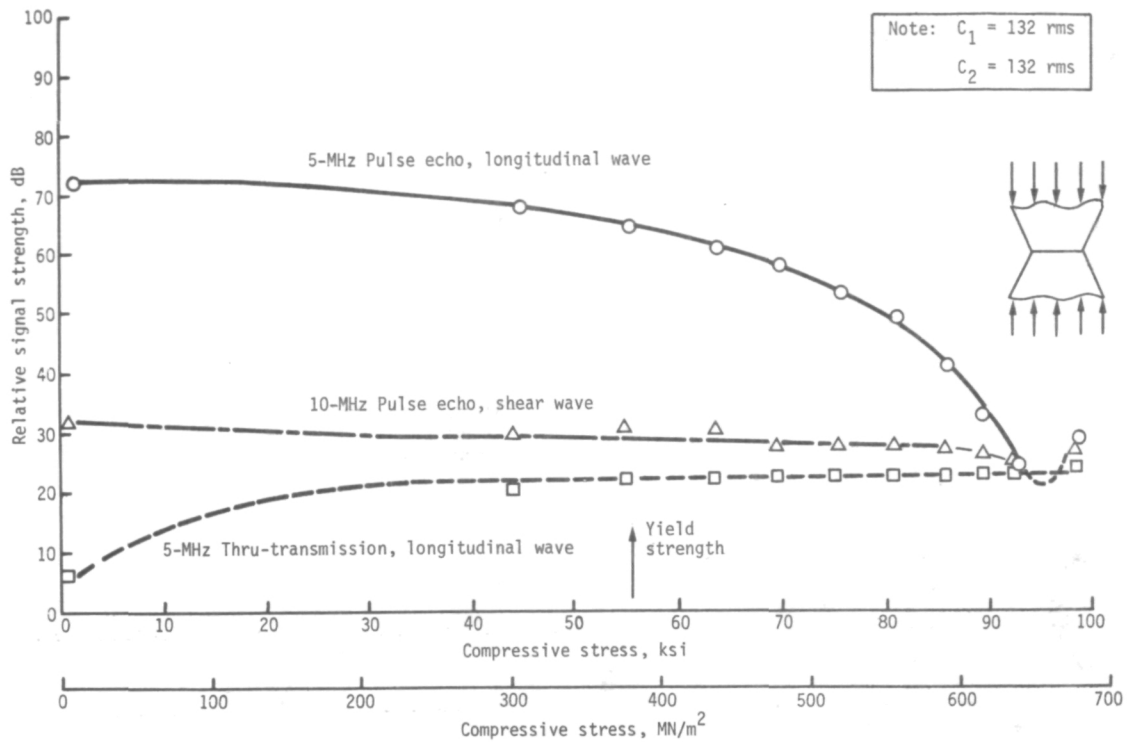


Figure 8. - Effect of compressive stress on room-temperature signal strength for coarse surface finish.

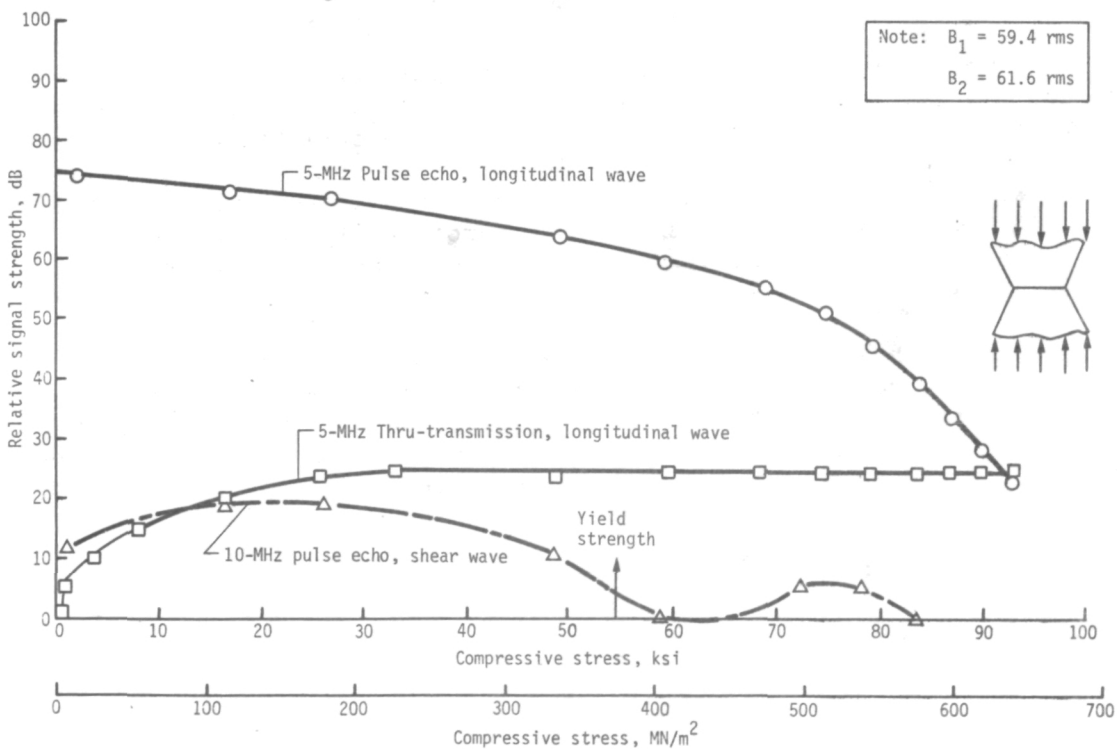


Figure 9. - Effect of compressive stress on room-temperature signal strength for medium surface finish.

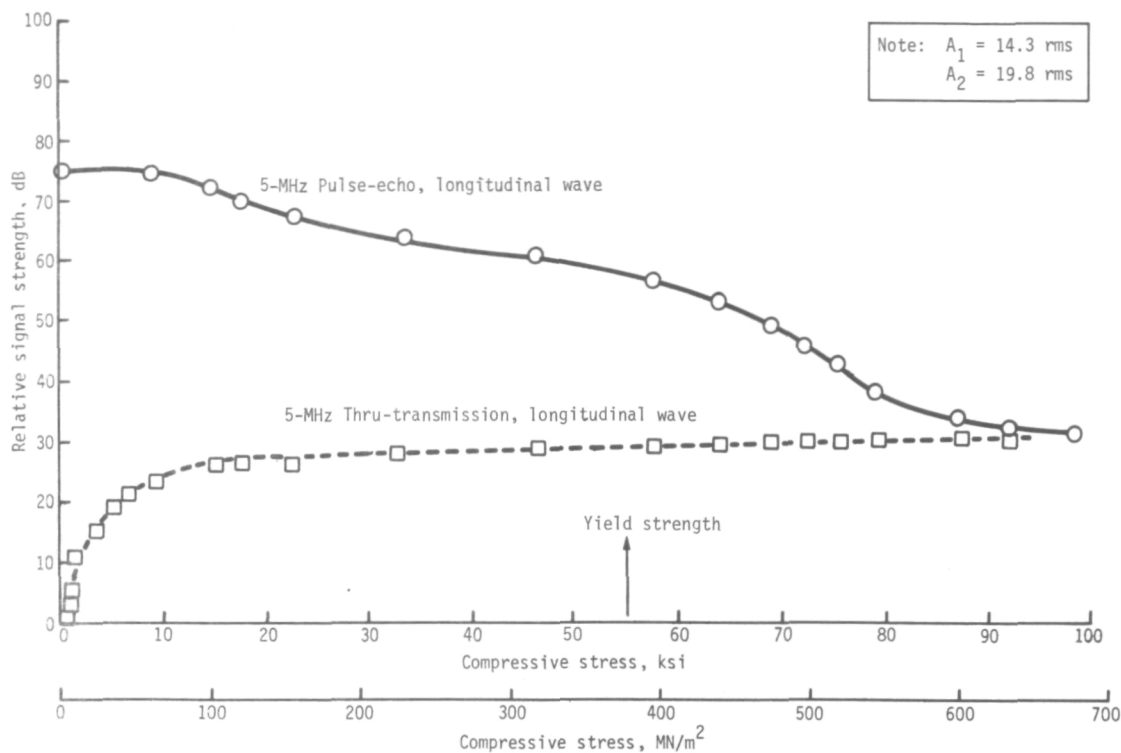


Figure 10. - Effect of compressive stress on room-temperature signal strength for fine surface finish.

The longitudinal-wave pulse-echo data showed a general decay of signal as the surfaces were pressed together. Through-transmission results showed a rather sharp increase in transmission as a function of load, but little further increase with additional load. The shear-wave method was load insensitive. The geometry of the specimen (truncated cone) was not readily amenable to shear-wave examination. On the basis of these results, the shear-wave method was dropped from the program.

The shapes of the through-transmission and pulse-echo curves were in general accordance with anticipated results because the differences in acoustic impedance of the relative media caused the initial reflected signal to be very large and the transmitted signal very small. Note that the signal amplitude expressed in decibels is:

$$dB = 20 \log \frac{A}{A_r} \quad (1)$$

where:

dB = decibel level,
 A_r = reference amplitude,
 A = measured amplitude.

For the reflected signal (pulse-echo method), the change in decibel level was small because the logarithm of the ratio of two numbers of similar magnitude becomes quite small. It is not until the reflection decreases significantly that the logarithm of their ratio becomes appreciable. Similarly, the ratio of the measured amplitude to reference amplitude for the transmitted signal shows a large initial change followed by a decreasing change in relative amplitude.

Radiographic inspection proved difficult. Very accurate alignment and ideal exposure conditions were required. The slightest misalignment of the beam resulted in loss of interface detection capability. Because of these alignment sensitivity problems, radiographic measurements were dropped from the effort.

The 422-K (300°F) test sequence was conducted in a manner similar to that used for room-temperature evaluation. Ultrasonic examination of the specimens was performed at room temperature. Centering and alignment of the specimens proceeded in the same manner. Each pair was centered, transducers aligned and locked in place. The specimen test section was then heated to 422 K (300°F) by an electric furnace surrounding the specimen test area. To determine when the specimen reached test temperature, a method was developed that would not interfere with the ultrasonic signal. The usual technique of using a buried couple was not satisfactory. The approach was to determine the time-temperature relationship for a dummy specimen with a buried couple and a surface-mounted couple near the faying surfaces. The surface-mounted couple was covered with an insulating pad to prevent its being affected by direct radiant heating. Using the relationship established between the surface and the internal temperature-time responses, the test specimens were heated using the surface couple for control.

As soon as the temperature in the faying surfaces region reached 422 K (300°F), the load was raised to generate the next compressive load increment. The assembly was then allowed to cool to room temperature while maintaining the same load level. The specimen was then inspected using pulse-echo and through-transmission techniques. Because of prolonged heating and cooling cycles, only three data points per specimen assembly were obtained. Through-transmission inspection of specimen assemblies was also deleted because the incremental load levels for through-transmission and pulse-echo inspection requirements were virtually pre-emptive, i.e., through-transmission changes in signal strength oc-

curred at low load levels where the pulse-echo signal was retaining its full strength, and the through-transmission signal remained constant at a high load level while the pulse-echo signal was changing drastically. Figures 11, 12, and 13 show test data for three surface roughnesses.

The 533-K (500°F) test data were generated in a manner similar to that for the 533-K (300°F) test sequence except that temperature was attained by using an acetylene torch to heat a shroud surrounding the specimen. Direct, localized heating of the specimen was thus avoided. Calibration of the temperature-time relationship for a surface versus a buried couple (as previously described) was used to provide a basis for temperature control. As soon as the specimen test area reached test temperature, the assembly was loaded and allowed to cool to room temperature at constant load using the load-control mode of the testing machine. The specimen was then examined. Figures 14, 15, and 16 show the results of this test sequence.

To simulate the lack-of-fusion defect condition, a compression block specimen assembly was modified by machining a 6.4-mm (0.25-in.) diameter by 0.08-mm (0.003-in.) deep indentation in one of the specimen surfaces (see fig. 17 for schematic of the specimen configuration). The intent was to track the disappearance and reappearance of the defect and to evaluate the compressive stress levels necessary to obscure an open defect. Figure 17 shows the results of this test sequence. Loading and unloading paths are indicated by arrows. The loading path was established by heating the specimen after the load was applied. As before, ultrasonic measurements were taken after the specimen cooled to room temperature. The unloading path was established at room temperature after the last loading cycle. The right-hand corner of figure 17 shows the contour of the faying surfaces after the test. Note that the original indentation created a protrusion in the bottom half of the specimen after the initial specimen loading, presumably filling the cavity and rendering it invisible as the stress across the specimen test area exceeded the material's yield strength. The originally flat faying surfaces changed to a convex outward profile as a result of increased yielding.

To ensure that the behavior of the indented compressive block was directly comparable to the flat specimens of identical surface finish, another compression-block specimen without the indentation was prepared and tested. The specimens halves were both flat at the faying surfaces. Figure 18 shows the contours of the flat specimens before and after the test run and the test results. Comparison of the loading curves for the two types of specimens shows a distinct dwell region [approximately between 69 MN/m² (10 ksi) and 345-MN/m² (50-ksi)] stress in the indented specimen (fig. 17), probably due to delay in closing the 0.08-mm

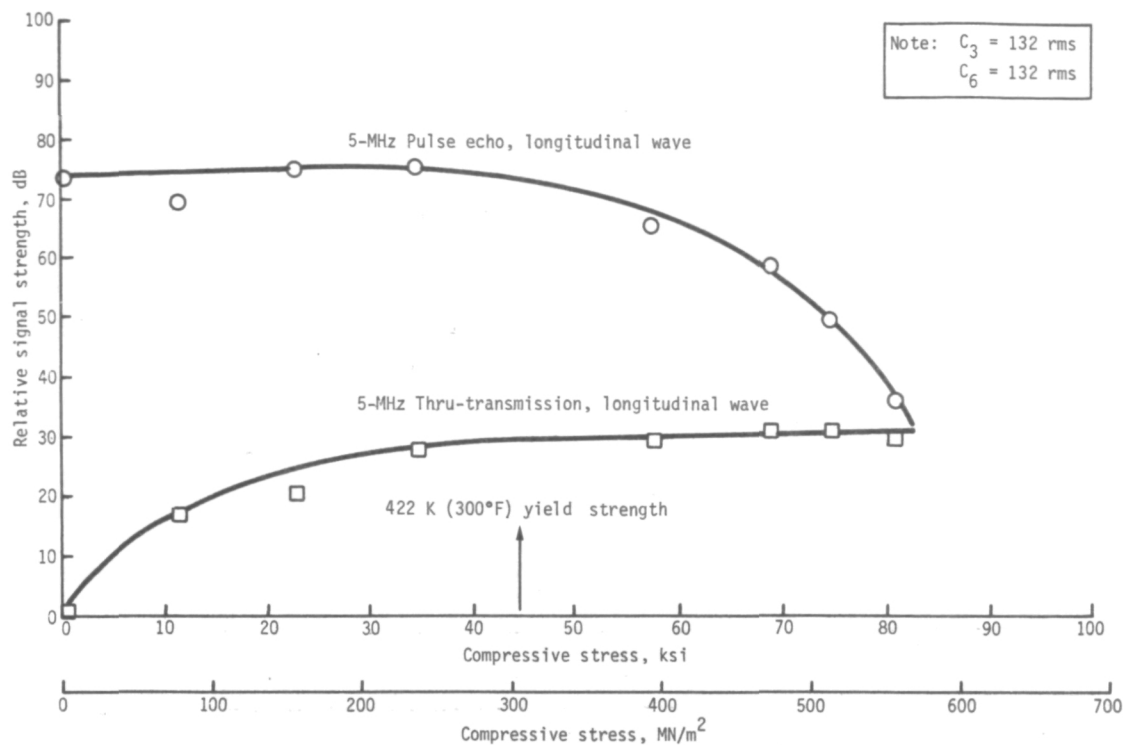


Figure 11. - Effect of compressive loading at 422 K (300°F) on room-temperature signal strength for coarse surface finish.

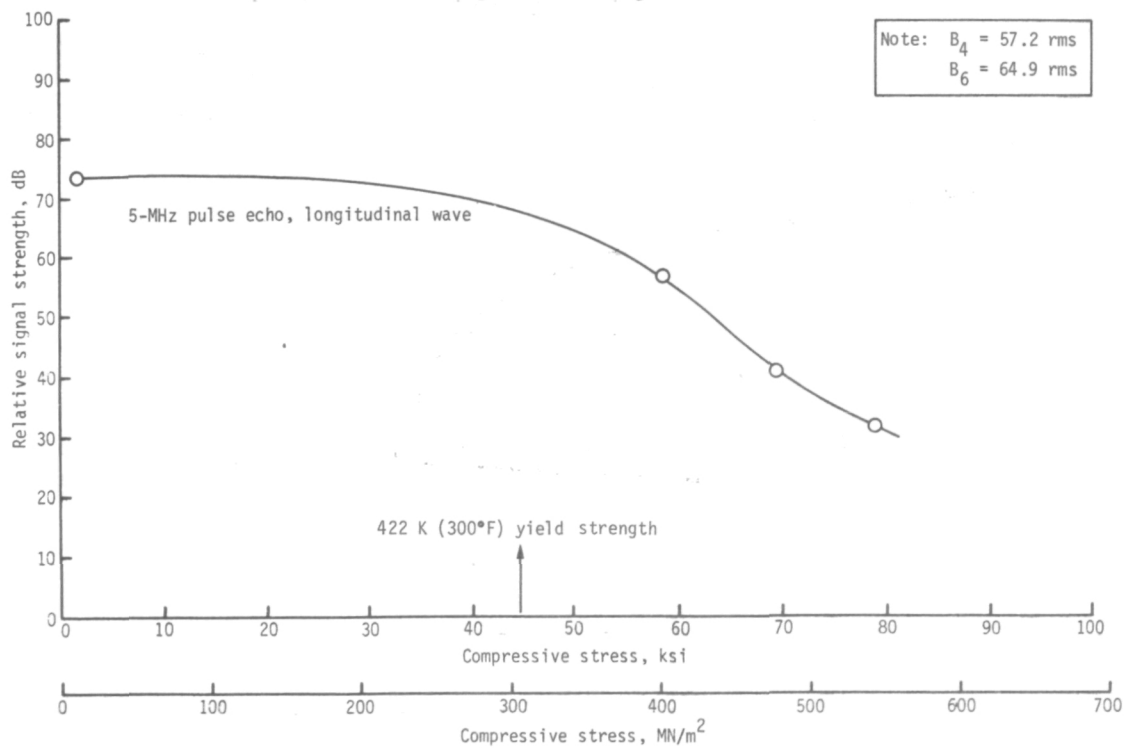


Figure 12. - Effect of compressive loading at 422 K (300°F) on room-temperature signal strength for medium surface finish.

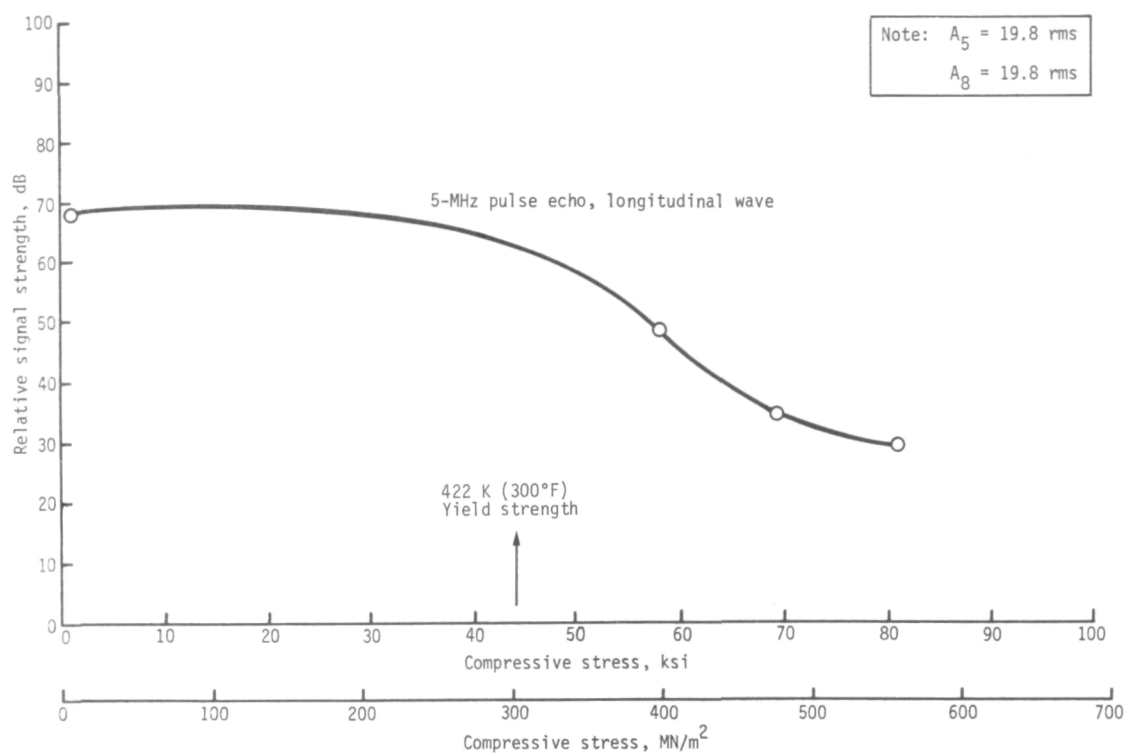


Figure 13. - Effect of compressive loading at 422 K (300°F) on room-temperature signal strength for fine surface finish.

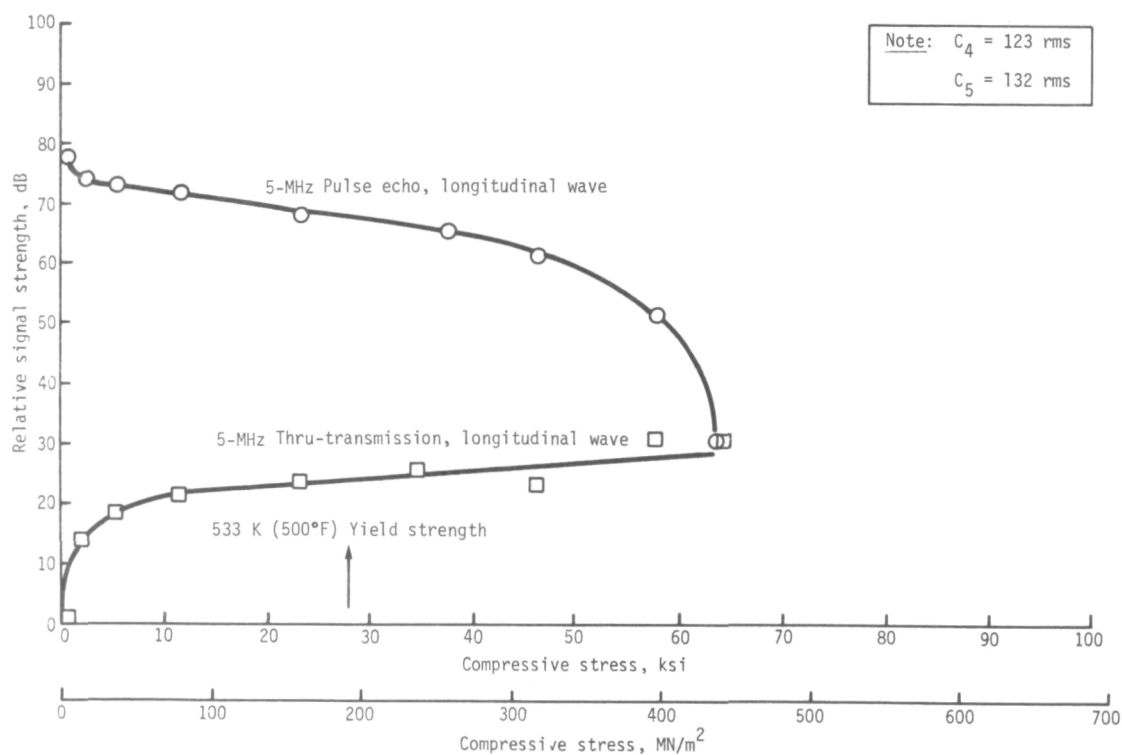


Figure 14. - Effect of compressive loading at 533 K (500°F) on room-temperature signal strength for coarse surface finish.

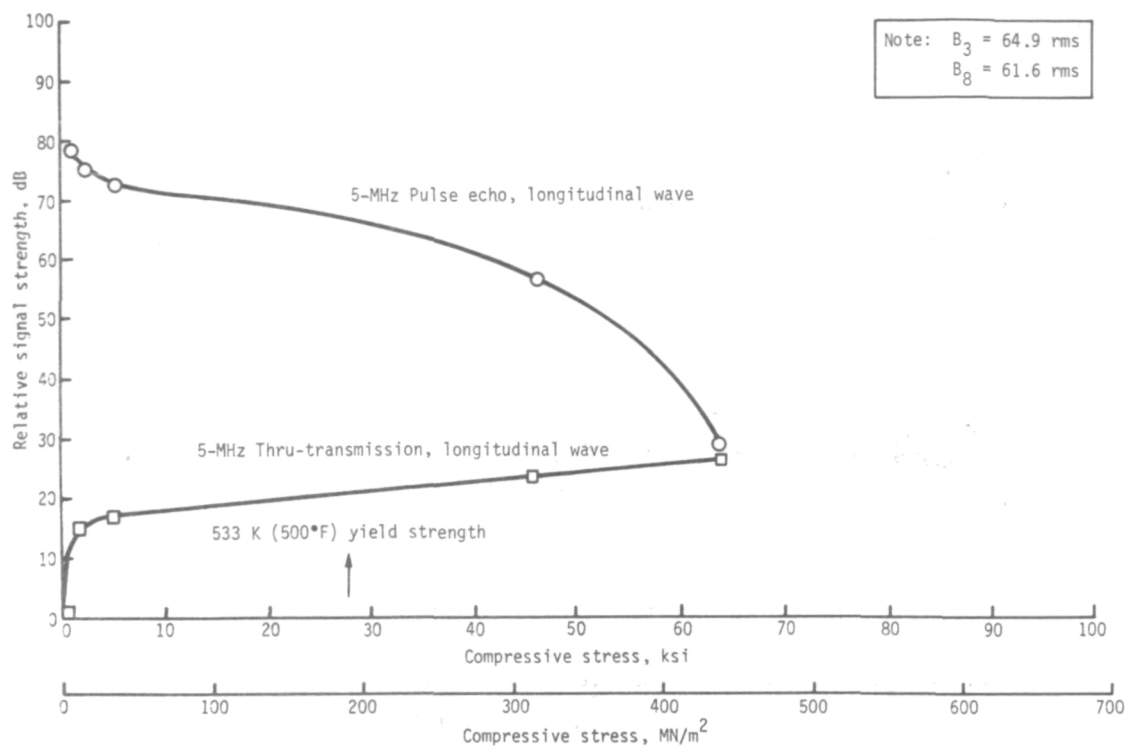


Figure 15. - Effect of compressive loading at 533 K (500°F) on room-temperature signal strength for medium surface finish.

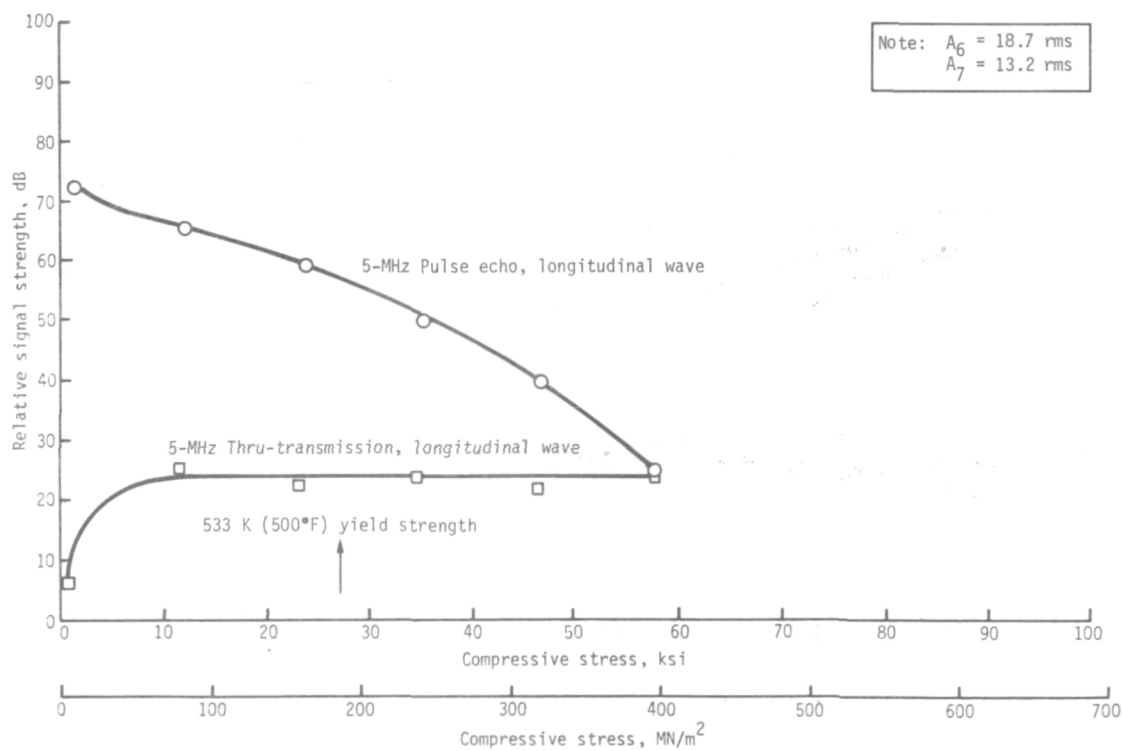


Figure 16. - Effect of compressive loading at 533 K (500°F) on room-temperature signal strength for fine surface finish.

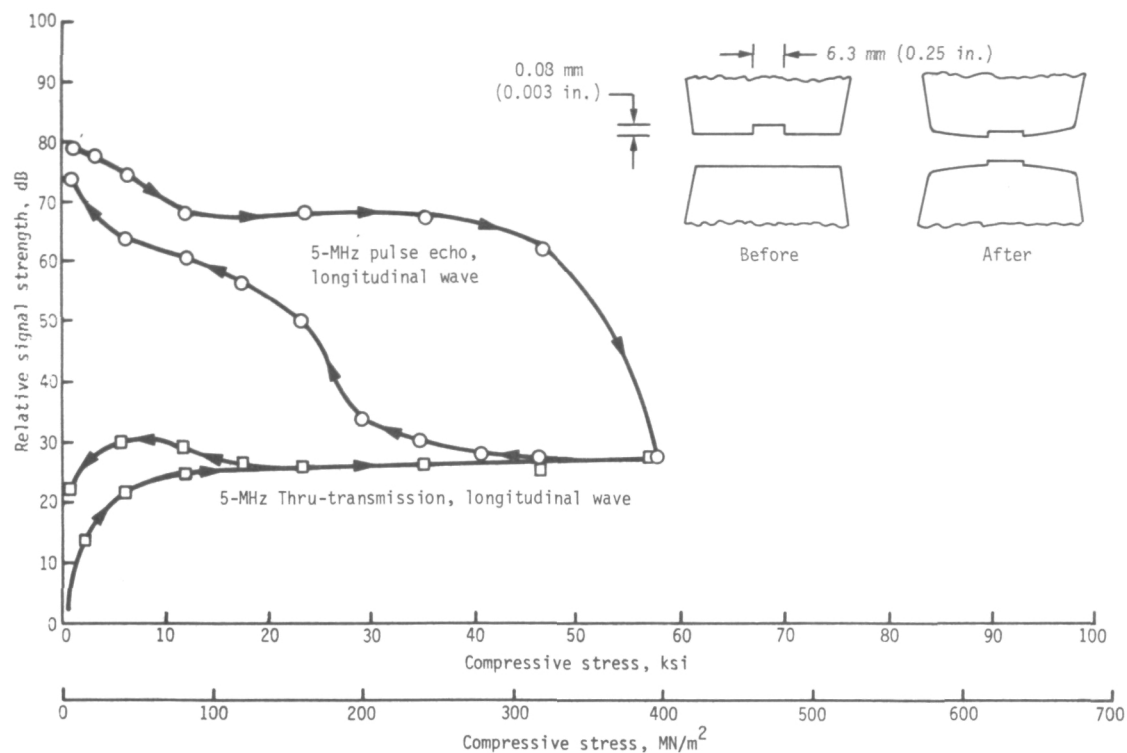


Figure 17. - Effect of compressive loading at 533 K (500°F) on room-temperature signal strength for simulated lack-of-fusion-defect specimen.

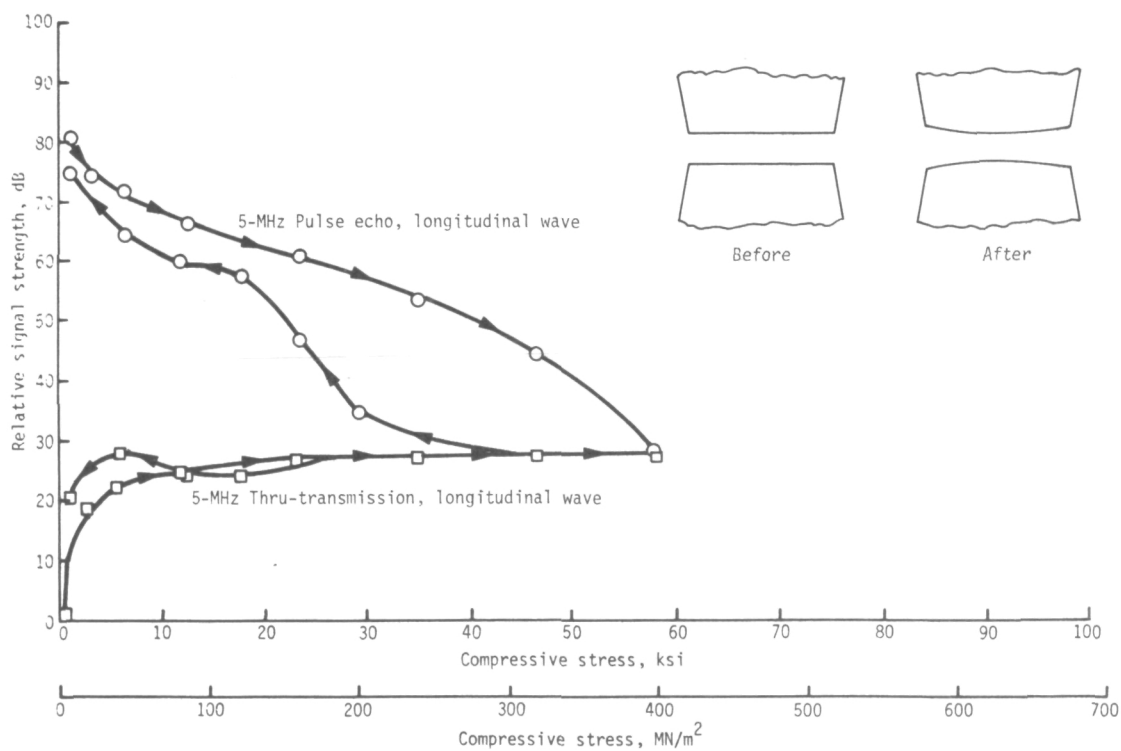


Figure 18. - Effect of compressive loading at 533 K (500°F) on room-temperature signal strength for flat-surface specimen.

(0.003-in.) indentation. No such dwell region can be seen in figure 18 for the flat specimen. Figure 19 compares the pulse-echo data curves for the two types of specimen. As shown in the figure, the unloading paths are remarkably similar, suggesting that once the faying surfaces were compressed beyond the material's yield strength, the unloading and opening of the faying surfaces resulted in the same strengthening of the pulse-echo signal.

Test results clearly show an effect of surface roughness on crack-closure behavior. As expected, the rougher surfaces require a greater force to cause decrease of signal strength than on the smoother surfaces. Although the effect is not great, it is obvious and consistent for data obtained after loading at each temperature. Figures 20, 21, and 22 show the effect of roughness on loss of signal for each loading temperature condition.

The loss of relative signal strength is related to temperature because of the decrease in yield strength with increasing temperature. Load versus deformation was plotted for each specimen. Based on the deviation of the load-deformation plots from linearity, a value for the room-temperature yield strength was obtained that agreed with data reported in table 1, and a value for the 422 K (300°F) yield strength was obtained that was in general agreement with the value of 310 MN/m^2 (45 ksi) reported in MIL-HDBK-5. At 533 K (500°F), it was not possible to establish the yield strength. Yield strength from published data for each temperature is noted in figures 8 through 16. It is seen that the curves show a general loss of signal starting at or above the point corresponding to the yield strength. The fact that loads well above yield strength are required to obscure the ultrasonic signal indicates that high levels of plastic deformation (a very tight defect) are required to develop an undetectable condition. This situation is comparable to that of welds containing defects. Residual stresses acting in the weld zone can be as great as the yield strength. An example of how tight a weld defect can be is shown by the fact that a scratch on one surface of a weld interface was coined into the mating surface, appearing in bas relief, in the process of making LFD weld joints.

The stress level required to obscure the interface decreased with increasing temperature, as shown by the plot in figure 23.

These results showed that forces in excess of the yield strength at room and evaluated temperatures were required to obscure the NDI ultrasonic indications of the faying surfaces of compressively loaded blocks. It was further evident that surface

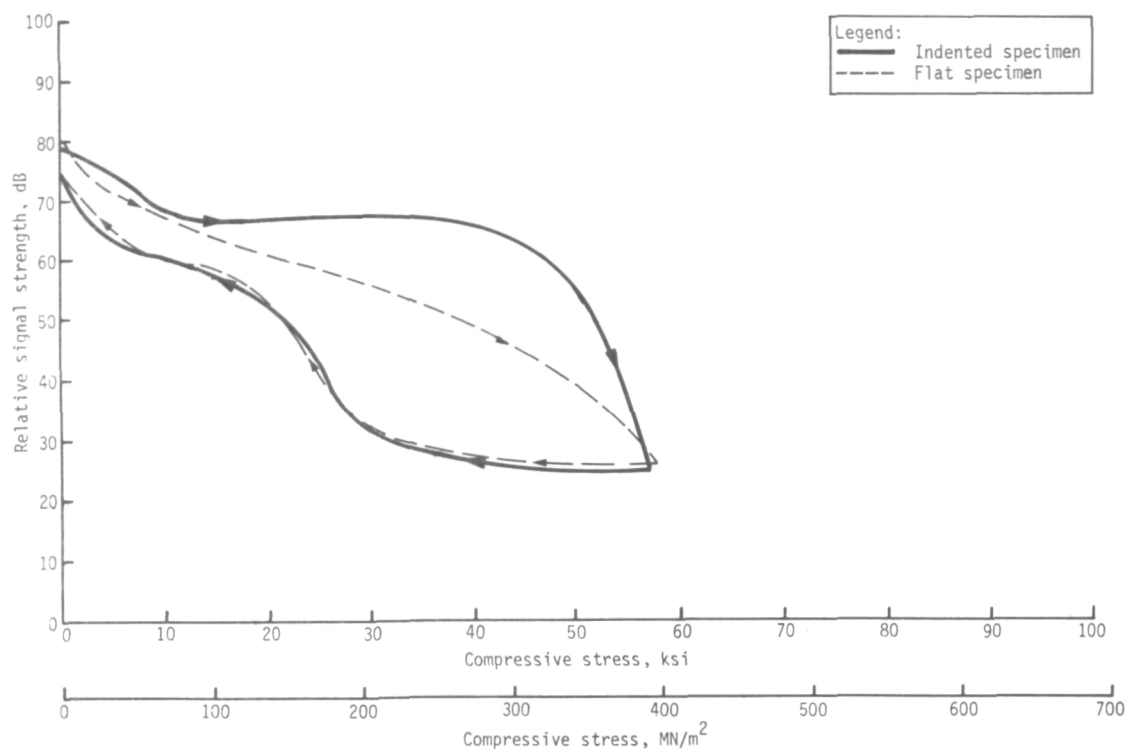


Figure 19. - Comparison of the effect of indented vs flat surface on signal strength.

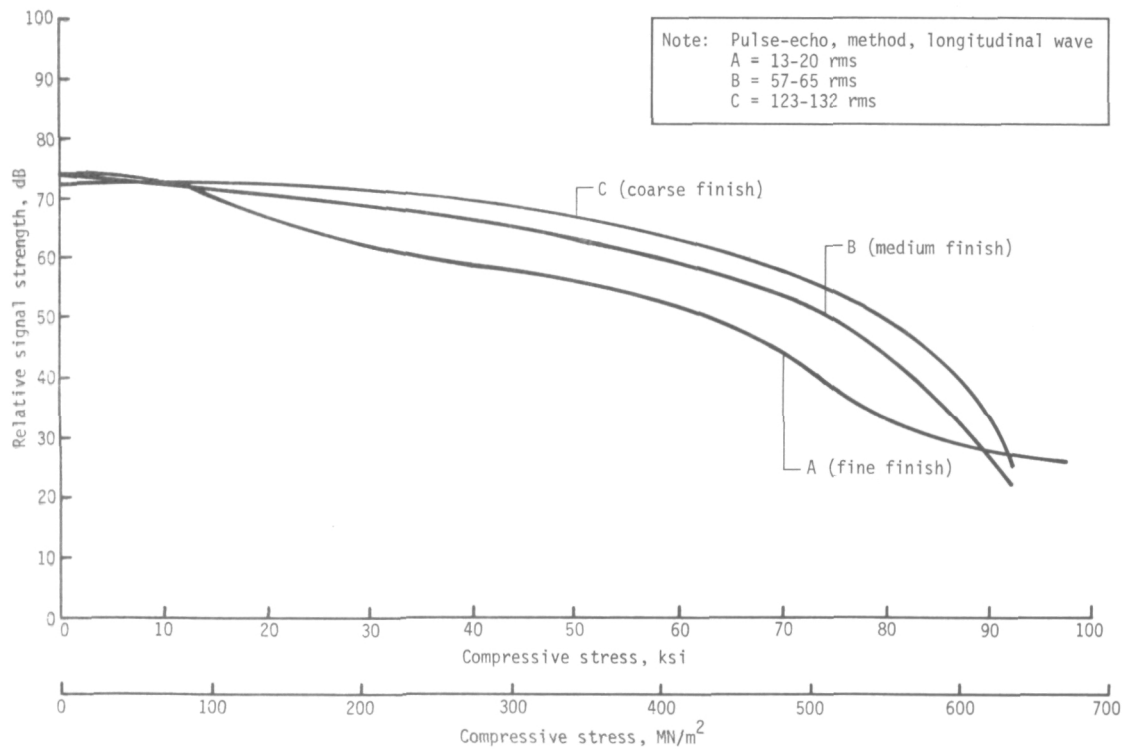


Figure 20. - Effect of surface finish on room-temperature signal strength.

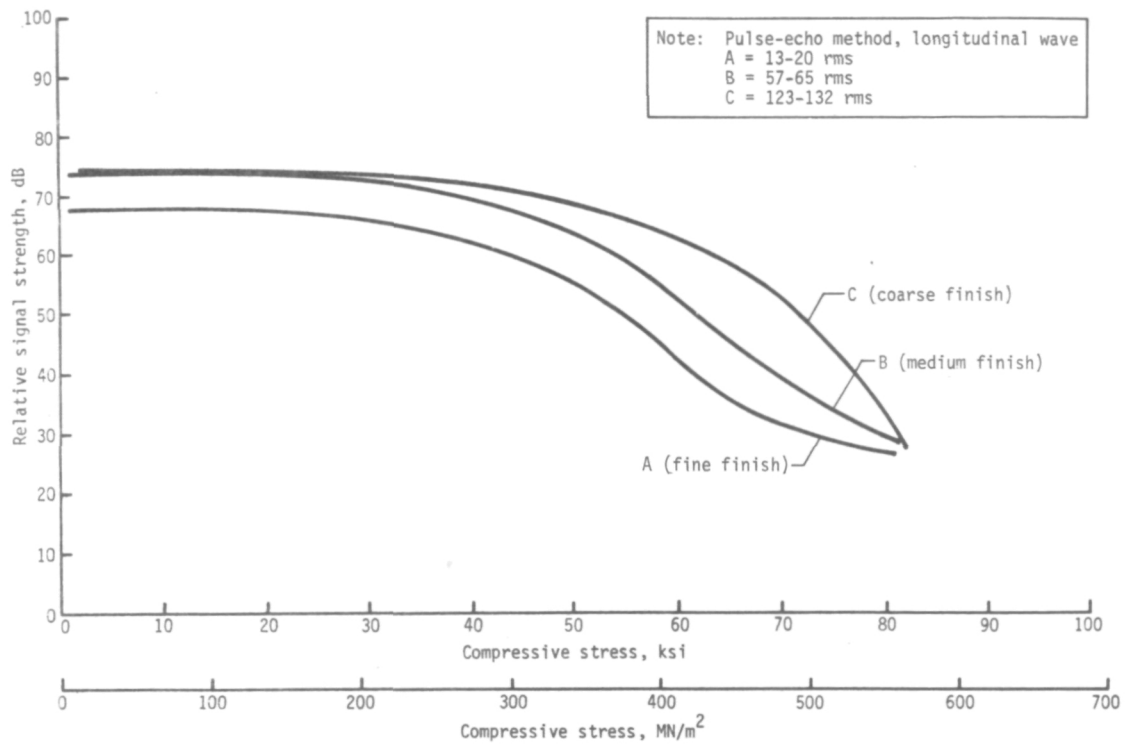


Figure 21. - Effect of surface finish on room-temperature signal strength [loading at 422 K (300°F)].

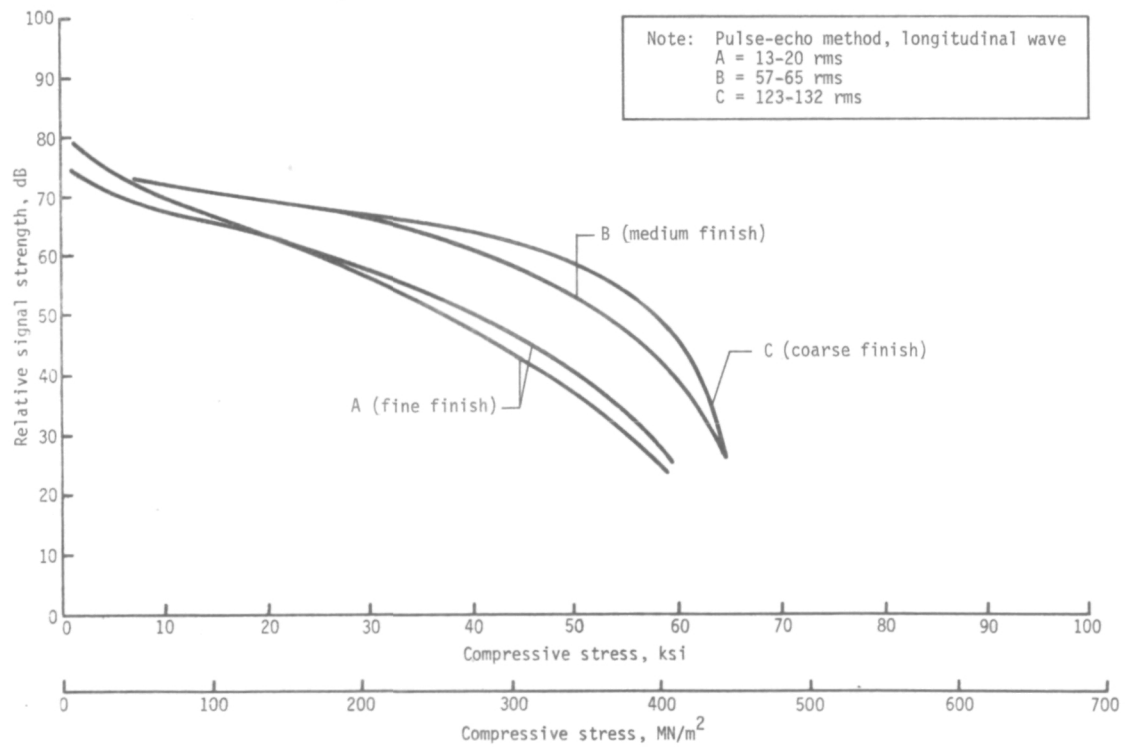


Figure 22. - Effect of surface finish on room-temperature signal strength [loading at 533 K (500°F)].

roughness did affect the force required to obscure the interface. Also, the force required to obscure NDI indications increased slightly with increasing surface roughness.

The results of this investigation are in agreement with a similar, but less detailed, study performed by Martin and Adams of McDonnell-Douglas (ref. 1). They first demonstrated that tight lack-of-fusion defects in welded 2014-T6 can go undetected by ultrasonic evaluation. In the second part of their study, they simulated lack of fusion by compressing two plates together and measuring signal strength using a pulse-echo, shear-wave technique. It was shown that application of forces below the yield strength did not obscure the interface. Figure 24 reproduces their data. Tests conducted at elevated temperatures, 665 K (740°F) and 700 K (800°F), also showed that the interface was not obscured at a force level corresponding to yielding. However, at 755 K (900°F), the interface transmitted all the ultrasonic energy.

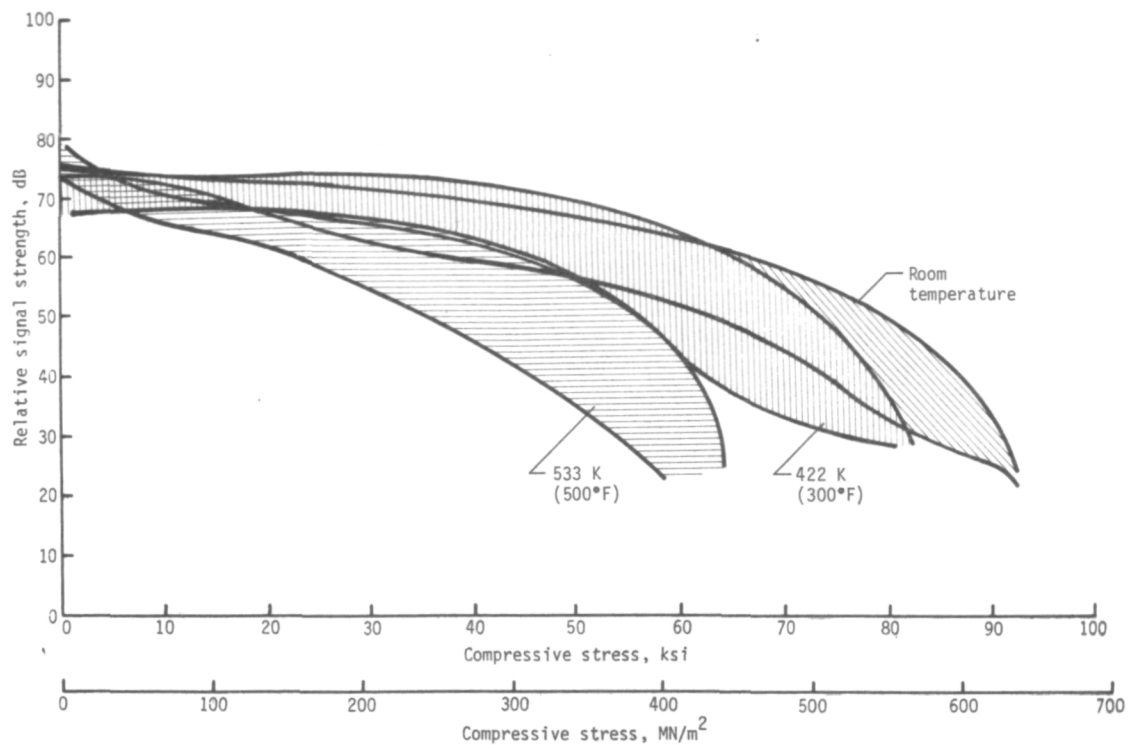


Figure 23. - Effect of temperature on signal strength.

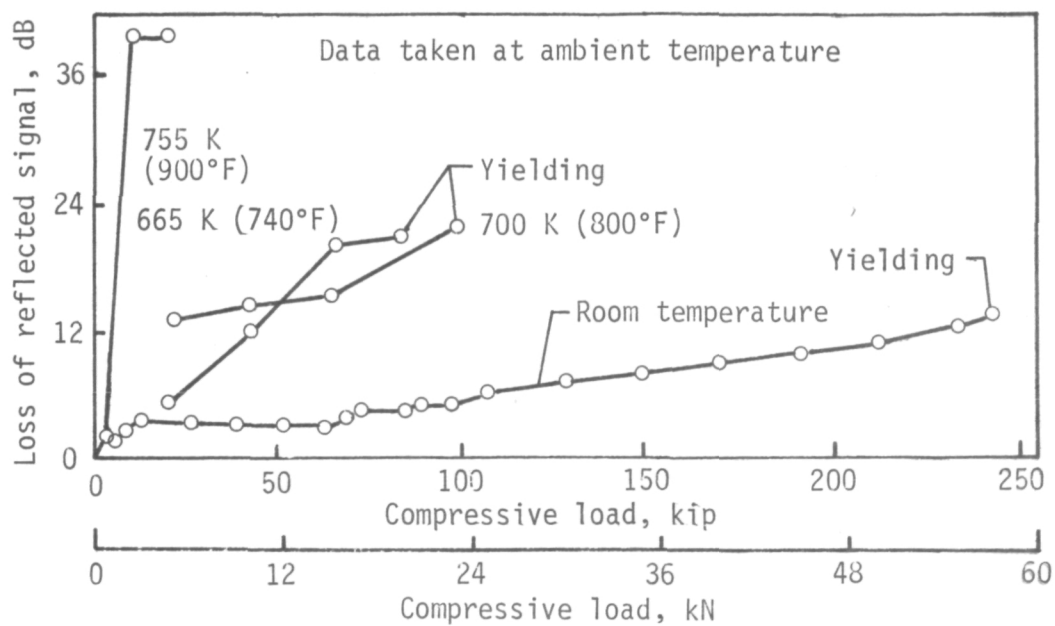


Figure 24. - Compressive load vs energy loss for abutted aluminum plates (from ref. 1).

DEVELOPMENT OF LACK-OF-FUSION DEFECT TEST SPECIMENS

The objective of this part of the program was to develop and perform a preliminary evaluation of lack-of-fusion weld specimens containing high levels of residual stresses.

Two types of specimens were prepared. One was a cylindrical specimen containing a circular lack-of-fusion defect oriented in the center of the specimen. The second was a flat panel containing a buried elliptically shaped defect.

Preliminary testing confirmed that proof loading was required to make tight defects detectable by NDI techniques. Radiographic inspection was generally unsatisfactory for identification of the presence of defects until full residual crack opening occurred. Even then, extreme care was required to identify defects.

Cylindrical Test Specimens

Specimen preparation. - Figure 25 shows the configuration of the weld blank used in this effort. Figure 26 shows the final weldment. All blanks were machined to achieve a nominal 63- μ m rms surface finish. Welding of the cylindrical parts was performed at the Rocky Flats Division of Rockwell International Corp. To obtain a defect contour free from instantaneous penetration variations (spiking), it was decided to offset the beam as shown in figure 27. Weld development was initiated using a 7.5-kW Hamilton Standard EB unit. Using this equipment, a penetration of 6.3 cm (2.5 in.) was obtained at a surface speed of 7.6 m/minute (3 in./minute) using full power. Excessive root porosity was apparent in this joint. Because of the possibility of reducing the residual stresses, multipass welding was not used.

A higher-power 30-kW Sciaky EB unit was used for additional development work. Although porosity could be controlled with a single-pass weld, defect shape control was poor. The specimen diameter was then reduced from the original 9.9 cm (3.9 in.) to 6.3 cm (2.5 in.) because the final specimen diameter would only be 5.1 cm (2.0 in.). Both good shape control and relative freedom from porosity occurred. Five specimens for preliminary evaluation were made in this manner. Evaluation of these specimens showed that some fine-pin-hole porosity ringed the lack-of-fusion defect. The remaining specimens were welded in a manner that attempted to eliminate the pin-hole porosity by withdrawing the beam to the outer portion of the specimen before sloping out the beam. Therefore, the difference between the two groups of specimens was: group 1 - beam was sloped out adjacent to defect; group 2 - beam was relocated away from defect, then sloped out.

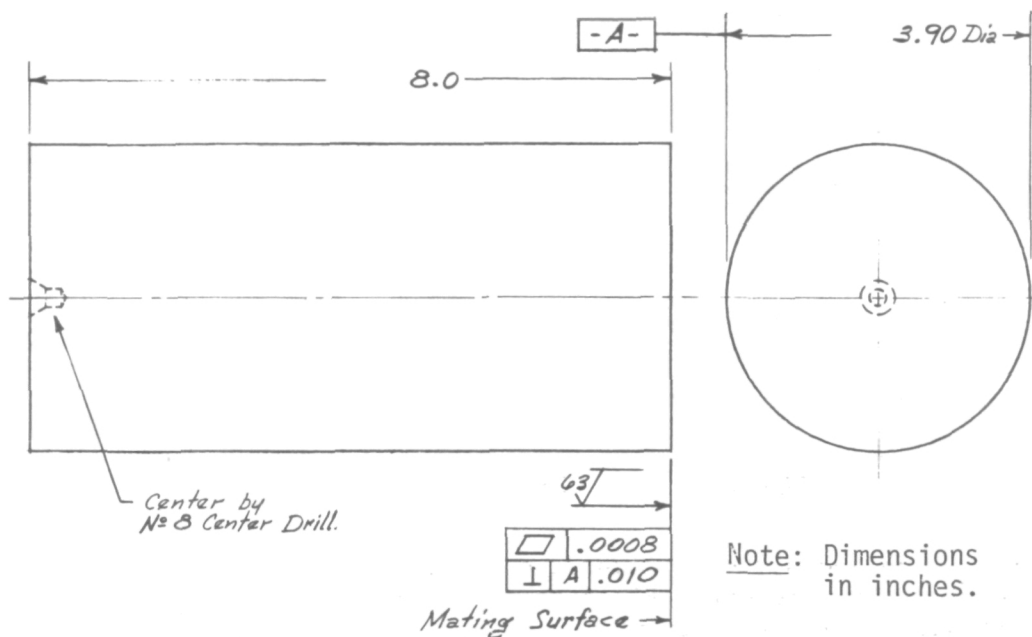


Figure 25. - Configuration of cylindrical weld blank.

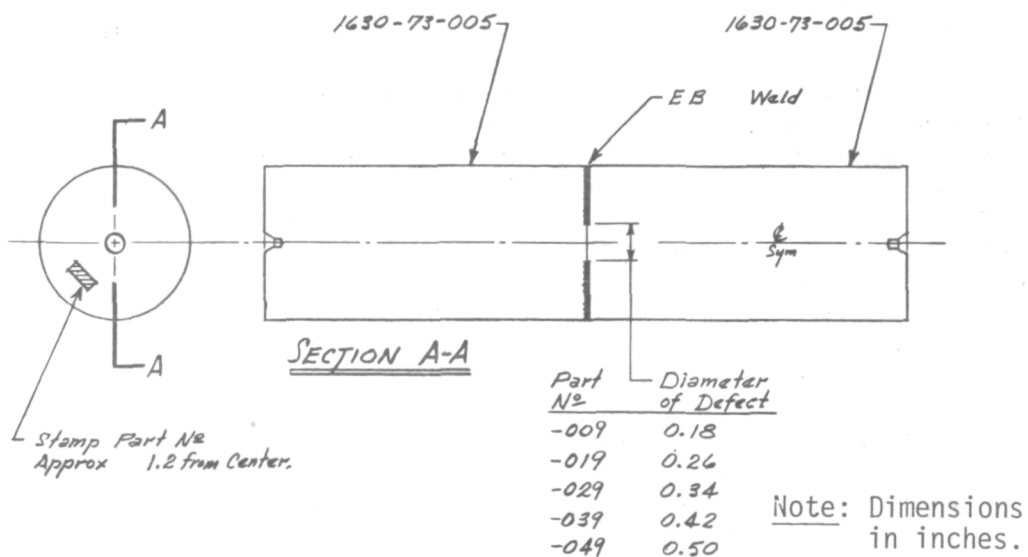


Figure 26. - Configuration of cylindrical weldment.

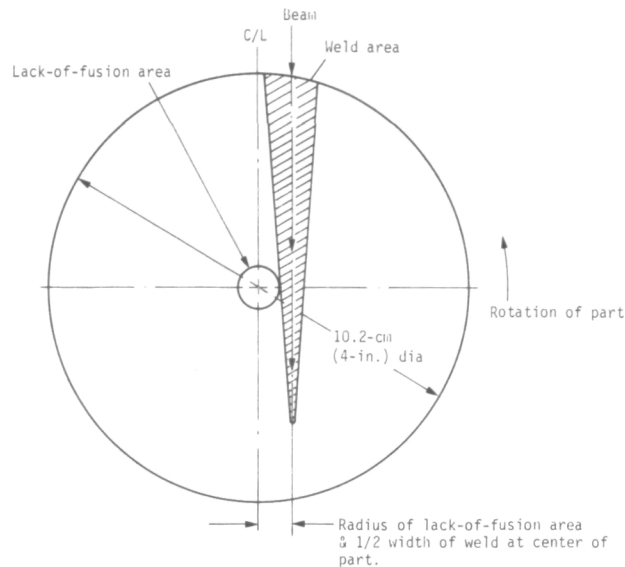


Figure 27. - Offset of weld beam.

Figure 28 shows the configuration of the test specimen machined from the weldment. Flats on the surface of the gage section were provided for instrumentation. Recesses in the grip area along the centerline of symmetry were provided for ultrasonic transducer coupling.

Equipment and Calibration.-- The ultrasonic equipment arrangement for this effort was the same as previously described for the crack closure studies. For tension testing, the specially made grips previously shown were used. Figure 29 shows a typical test specimen installed in the 4.45-MN (1 000 000-lb) MTS machine.

Calibration of the pulse echo equipment was achieved using a reference-block specimen containing a 6.3-mm (16/64-in.) diameter hole. The reflected signal was monitored by introducing a 93-ohm attenuator (0 to 122 dB) into the circuit. The resistance of the circuit was adjusted until a signal with a 5.7-cm (2-in.) amplitude appeared on the screen. This technique was used for all test conditions; i.e., monitoring of behavior for different testing conditions was achieved by adjusting the resistance of the circuit until a 5.7-cm (2-in.) high signal appeared on the scope. The resistance change was directly relatable to decibel change.

Preliminary Tests. - The first five specimens were used to confirm the procedural techniques, obtain preliminary data regarding the force required to overcome crack closure, and check dimensional correspondence of defect size to the desired sizes.

Samples were installed in the 4.45-MN (1 000 000-lb) machine and monitored by ultrasonic longitudinal-wave pulse-echo and in a

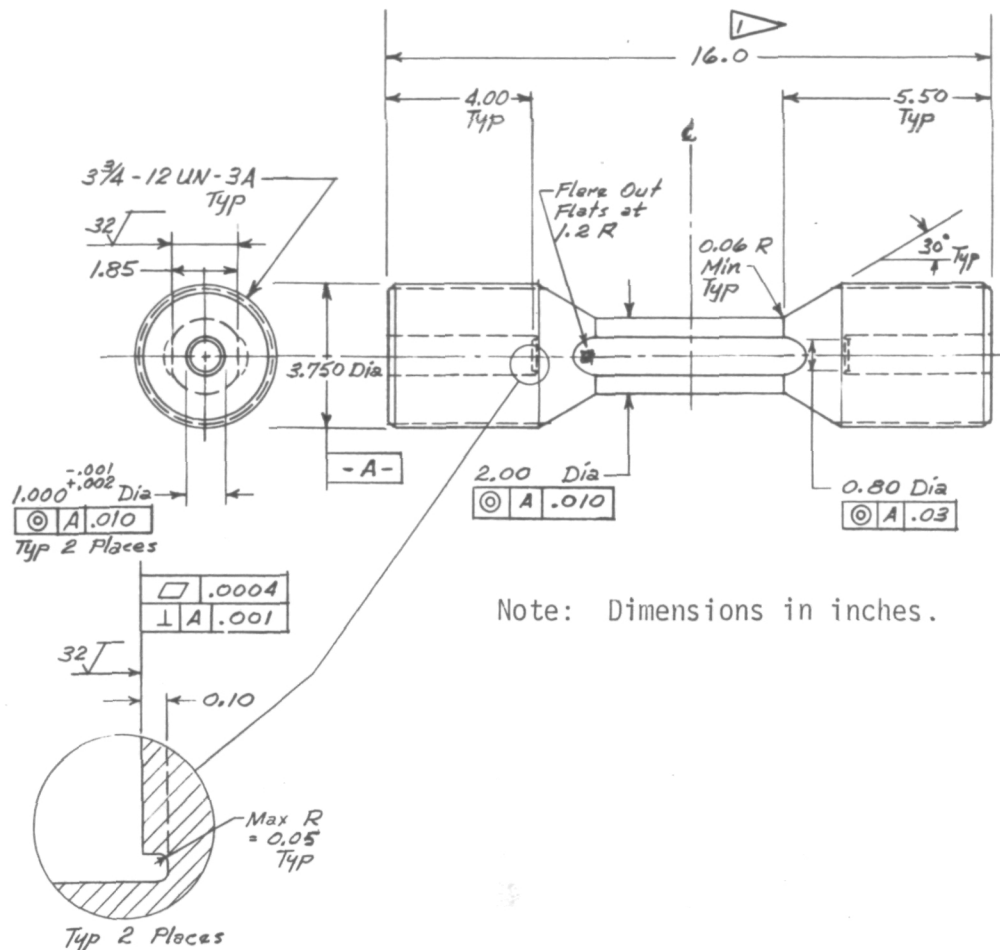


Figure 28. - Configuration of cylindrical test specimen.

limited manner by through-transmission techniques at 5 MHz and shear-wave pulse-echo at an incident angle of 45° using a frequency of 10 MHz.

Figure 30 shows the results of the first test specimen, R-1, [4.8-mm (3/16-in.) nominal defect diameter]. Data plots are for the longitudinal-wave pulse-echo technique. The initial reading before run 1 was 14 dB. The specimen was incrementally loaded and ultrasonic strength readings taken. At 11 MN/m² (1.6 ksi) and 22 MN/m² (3.2 ksi), the initial reading of 14 dB was unchanged. Loading to 34 MN/m² (5 ksi) caused a decrease in signal until, above 70 MN/m² (10 ksi), the signal abruptly rose to 20 dB. As loading progressed to 81 MN/m² (12 ksi), signal strength stabilized at the 21-dB level.

Because of the unanticipated behavior, it was decided to unload incrementally and monitor signal strength. Arrows on the figures show loading and unloading paths. During unloading, decay of signal strength was gradual until 34 MN/m² (5 ksi) was

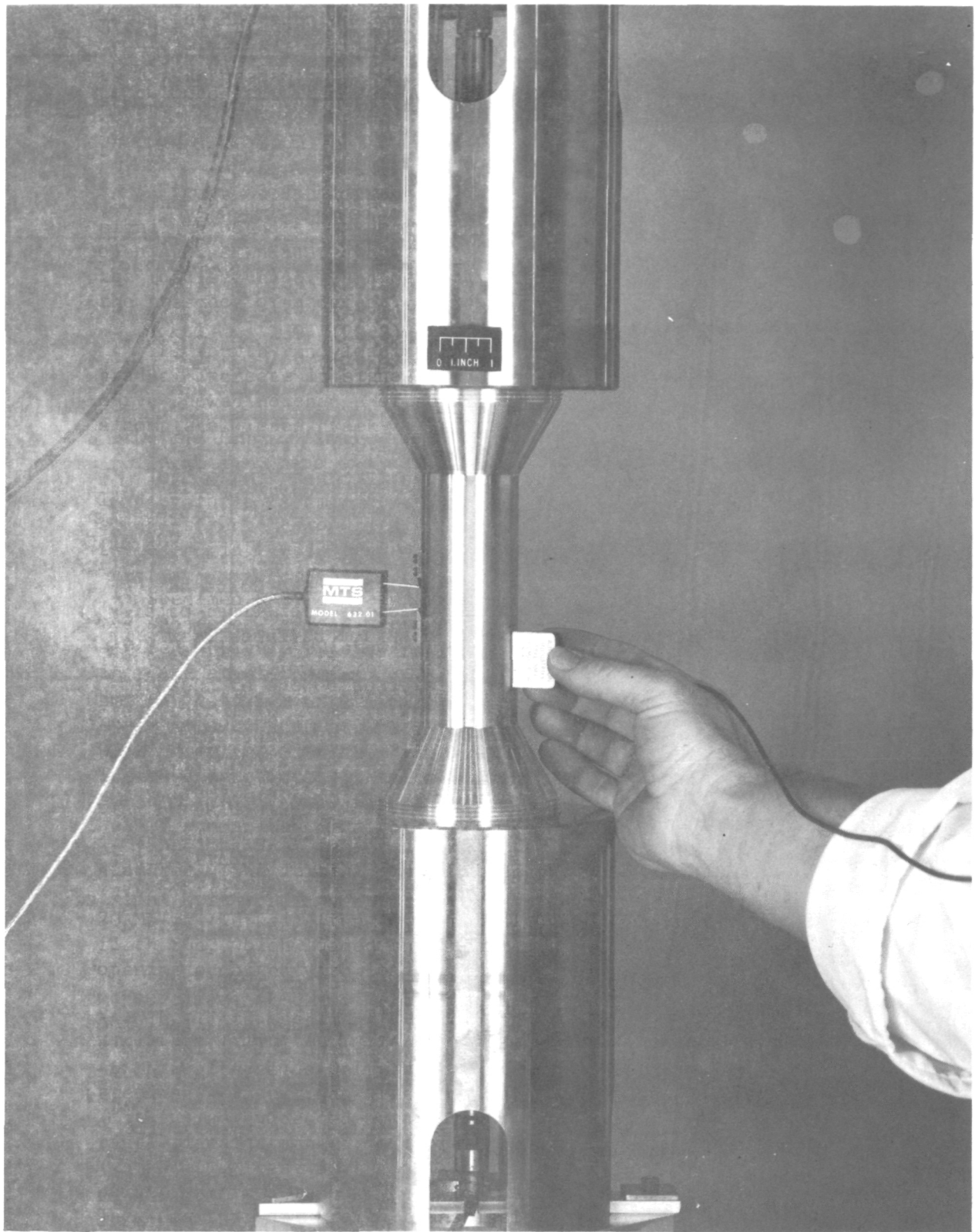


Figure 29. - Cylindrical specimen installed in testing machine.

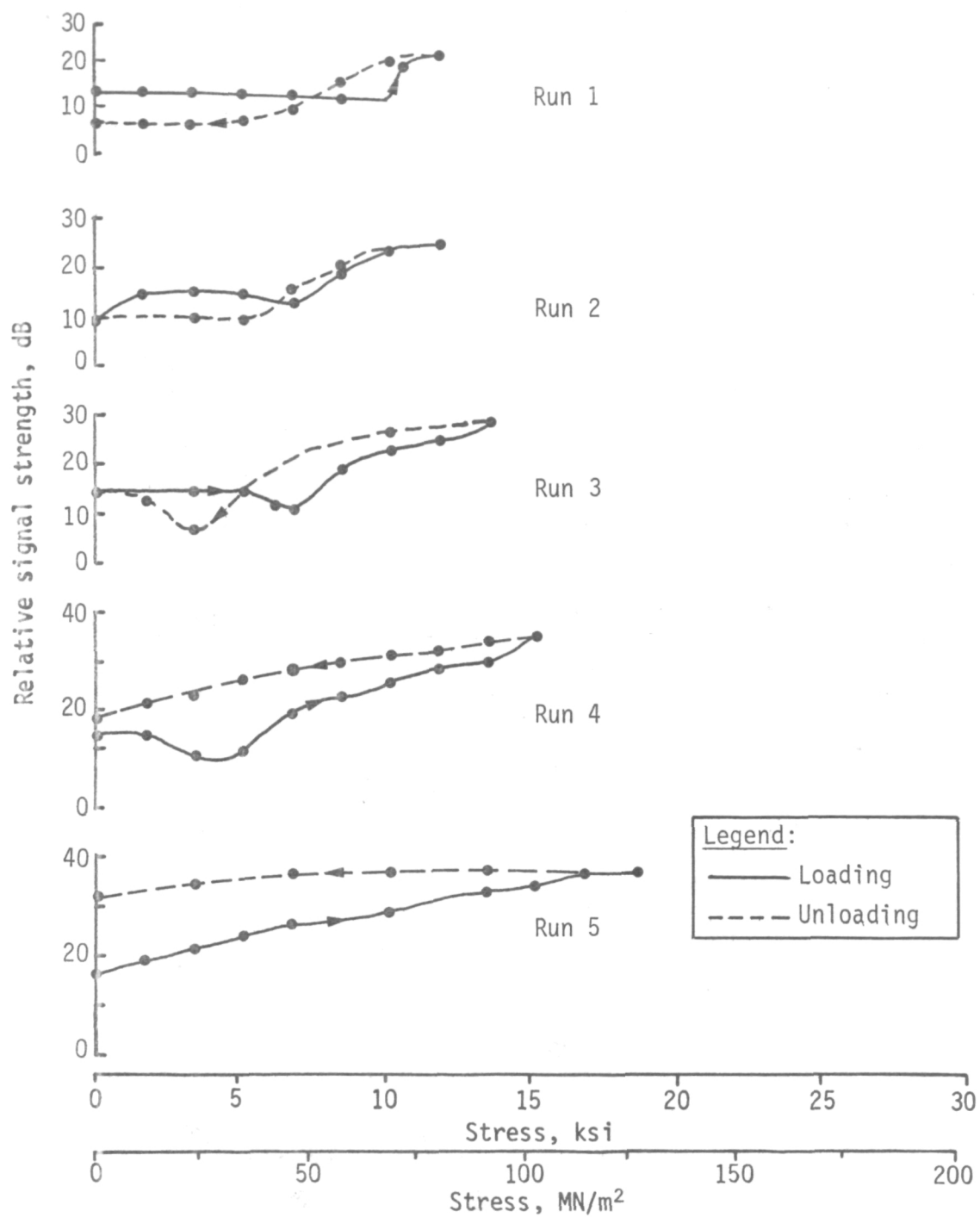


Figure 30. - Effect of loading on signal strength (specimen R-1).

reached. Below this level, no change in signal strength was noted. The final signal strength level was lower than the initial level--another unanticipated phenomenon.

The second run started at the unload level of the previous run (about 8 dB). On loading to 11 MN/m² (1.6 ksi), the signal reached the original 14-dB level. From this point, signal strength repeated the former pattern until, at 46 MN/m² (7 ksi), it began to increase gradually. Signal strength increased progressively without evidence of any sudden signal strength changes. At 81 MN/m² (12 ksi), the specimen was incrementally unloaded. As in the first run, the unloading curve dipped below the loading portion.

The results of the third load sequence showed a higher initial signal strength than that detected at the end of the previous run. This was probably caused by repositioning of the ultrasonic transducer after an overnight interruption of the test series. A dip in the curve at 46 MN/m² (7 ksi) during loading was noted; a similar dip was apparent at 23 MN/m² (3.5 ksi) during unloading. No reason for this behavior was apparent.

Run 4 showed a dip between 22 MN/m² (3.2 ksi) and 34 MN/m² (5 ksi), followed by a general increase in signal strength to 105 MN/m² (15 ksi). Unloading proceeded almost linearly, with a slight increase above the initial value at zero load (indicating a small amount of residual defect opening).

The final test run on this specimen consisted of loading to 127 MN/m² (18 ksi). The loading curve was essentially linear, and the unloading curve was almost flat. The residual signal was at 31 dB after unloading--approximately 15 dB higher than the initial value, indicating full crack opening.

Radiographic examination was performed after each test sequence to determine the degree of opening required to permit x-ray detection. Despite the care taken to center the x-ray beam parallel to the interface, no evidence of the presence of the defect could be found until unloading after the last test sequence. Even then, extreme care in alignment as well as careful film examination were required to attain detectability.

Testing of the second specimen (R-2) containing a nominal 6.4-mm ($\frac{1}{4}$ -in.) diameter lack-of-fusion defect proceeded in a manner similar to the sequences previously described. Figure 31 summarizes the results. A flat response was obtained until, at 65 MN/m² (9 ksi), a sudden jump occurred. This was anticipated, and loading terminated at this point. The unloading curve was gradual, returning to the initial strength level at zero load.

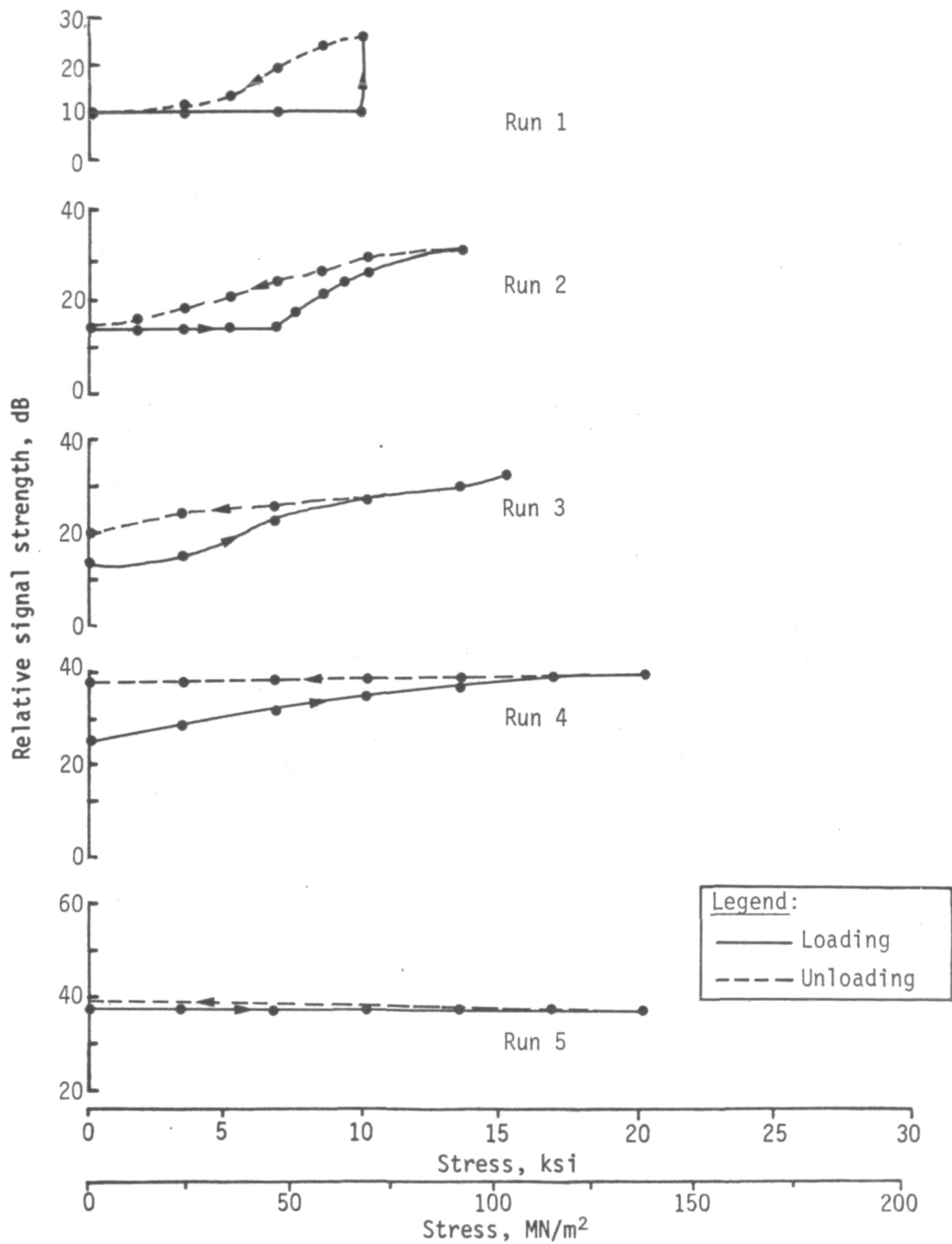


Figure 31. - Effect of loading on signal strength (specimen R-2).

The second sequence was used to load to 93 MN/m^2 (14 ksi). Because of transducer repositioning, the initial level was slightly higher than that at the end of the previous run. The signal remained constant until a load of 46 MN/m^2 (7 ksi) was reached; at this point, the ultrasonic signal increased rather rapidly but not suddenly. The unloaded curve was gradual, returning to the initial signal level at zero load.

The third run showed a gradual increase and decrease of the signal throughout the entire loading curve. A residual crack opening was indicated by a 6-dB increase in signal strength after the load sequence. Radiographic examination failed to indicate the presence of a defect.

The fourth run, loading to 139 MN/m^2 (20 ksi), showed a gradual increase in signal during rising load. The unloading curve showed no change of signal strength with stress, indicating a completely open crack. X-ray failed to identify a defect.

The fifth run was performed to establish the effect of re-loading to 139 MN/m^2 (20 ksi) on signal behavior. No change in signal strength from the final value of the previous run was detected during this series.

Specimen R-3, containing a 7.9-mm (5/16-in.) nominal defect was subjected to load sequences similar to those previously described. Figure 32 shows the test results--a sudden signal increase at 65 MN/m^2 (9 ksi) during the first run. Specimen R-2 exhibited the same behavior at the same load. The force required to develop signal-strength behavior indicating residual crack-opening displacement was 105 MN/m^2 (15 ksi). Full opening was achieved by loading to 125 MN/m^2 (18 ksi). Radiography was again ineffective until the defect was fully open.

Specimen R-4 contained a defect with 9.5-mm (3/8-in.) nominal diameter. The initial signal strength jump occurred at 46 MN/m^2 (7 ksi) (fig. 33). No residual opening was found for loads up to 70 MN/m^2 (10 ksi) (run 4). Initial opening occurred during the fifth run, which loaded the specimen to 105 MN/m^2 (15 ksi). Full opening occurred with loading to 139 MN/m^2 (20 ksi).

The fifth specimen (R-5) of the first series had a nominal diameter of 11.1 mm (7/16 in.). The initial jump was observed at 46 MN/m^2 (7 ksi). Only three runs were used to evaluate this specimen. Significant residual opening was found at 105 MN/m^2 (15 ksi) as evidenced by a large difference between initial and final signal strength. Complete opening occurred at 127 MN/m^2 (18 ksi). Figure 34 summarizes the data. The longitudinal-wave pulse-echo technique was the most sensitive to changes in stress. The longitudinal through-transmission and shear-wave pulse-echo techniques showed little stress dependency and were not further

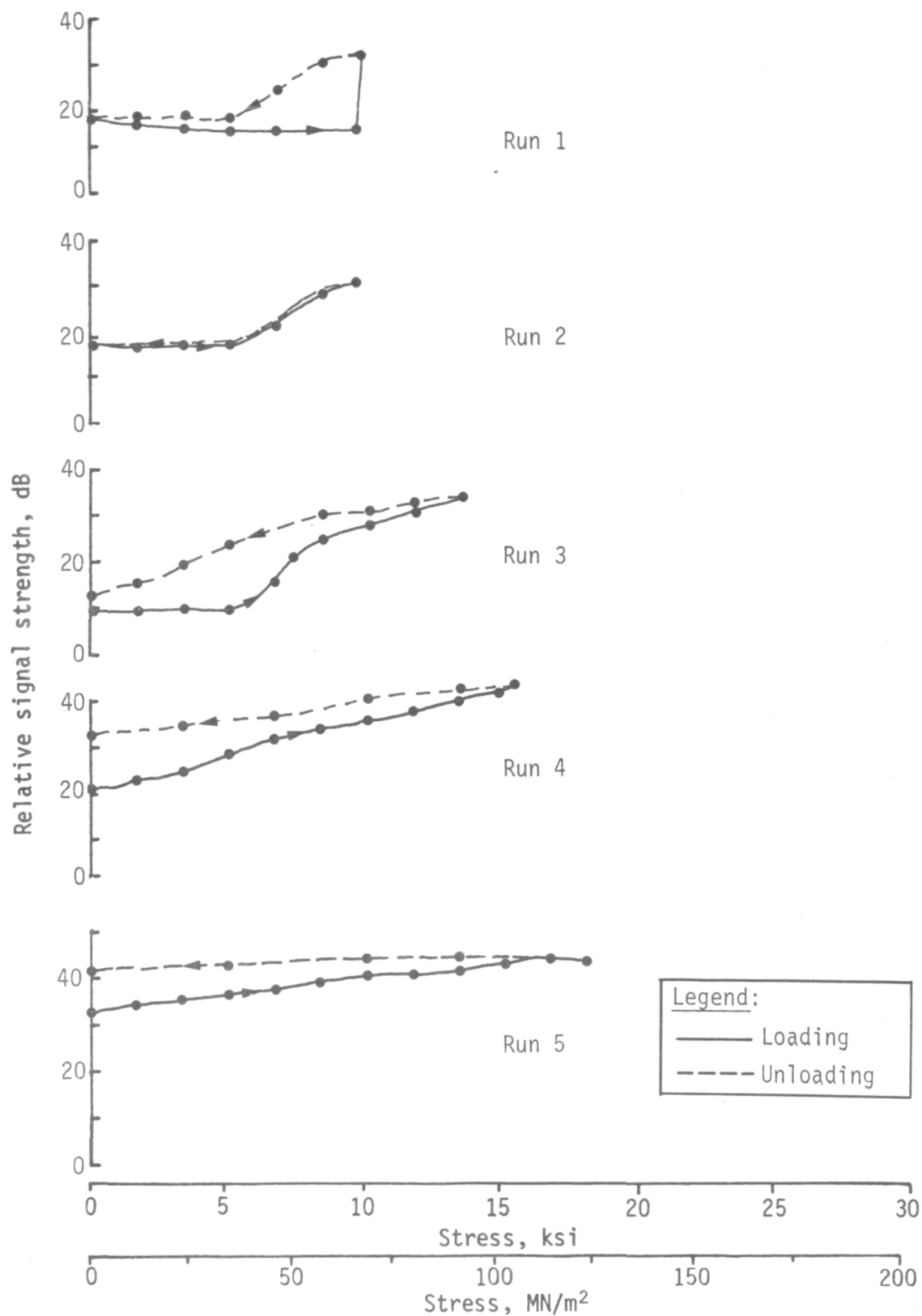


Figure 32. - Effect of loading on signal strength (specimen R-3).

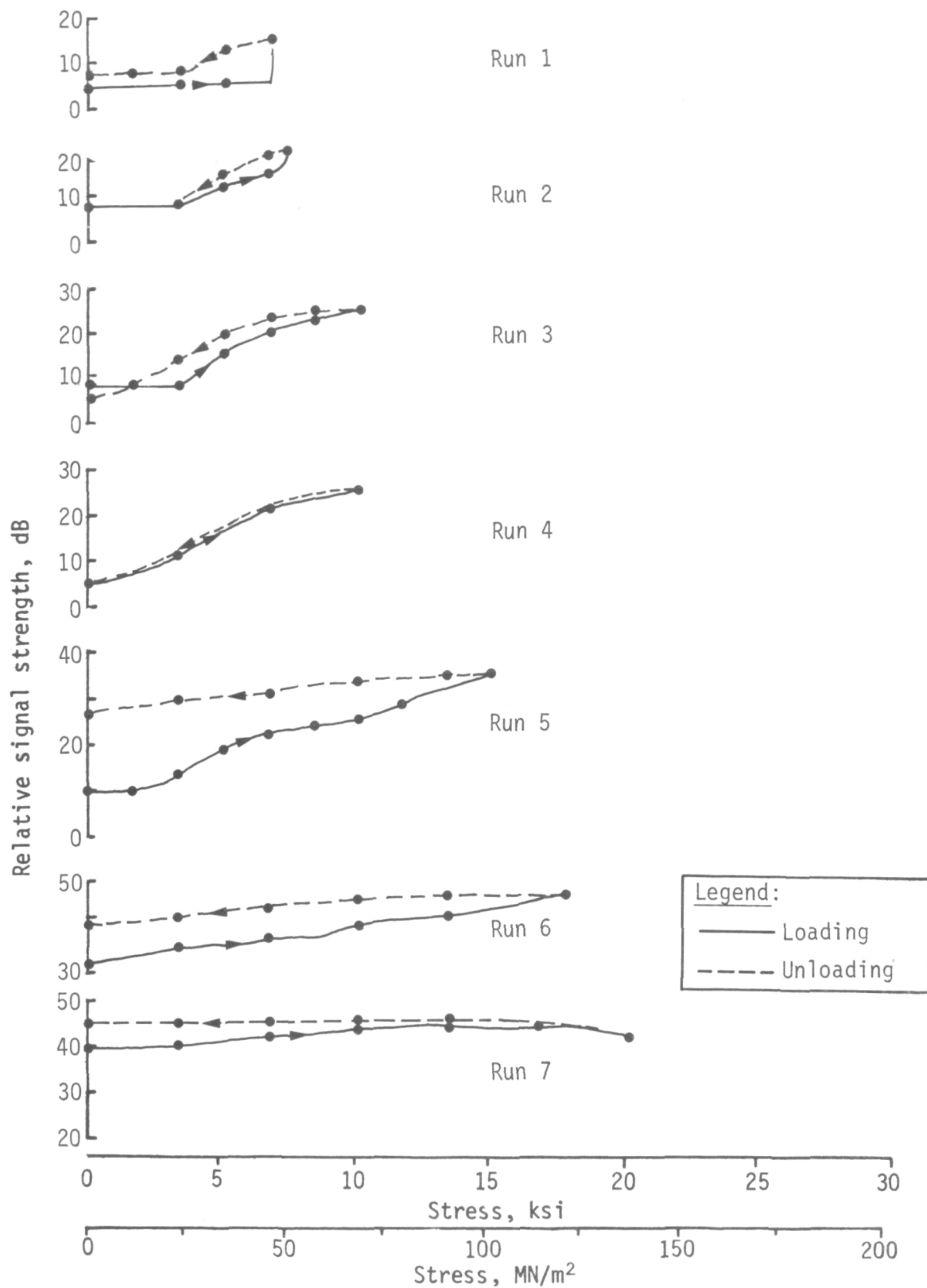


Figure 33. - Effect of loading on signal strength (specimen R-4).

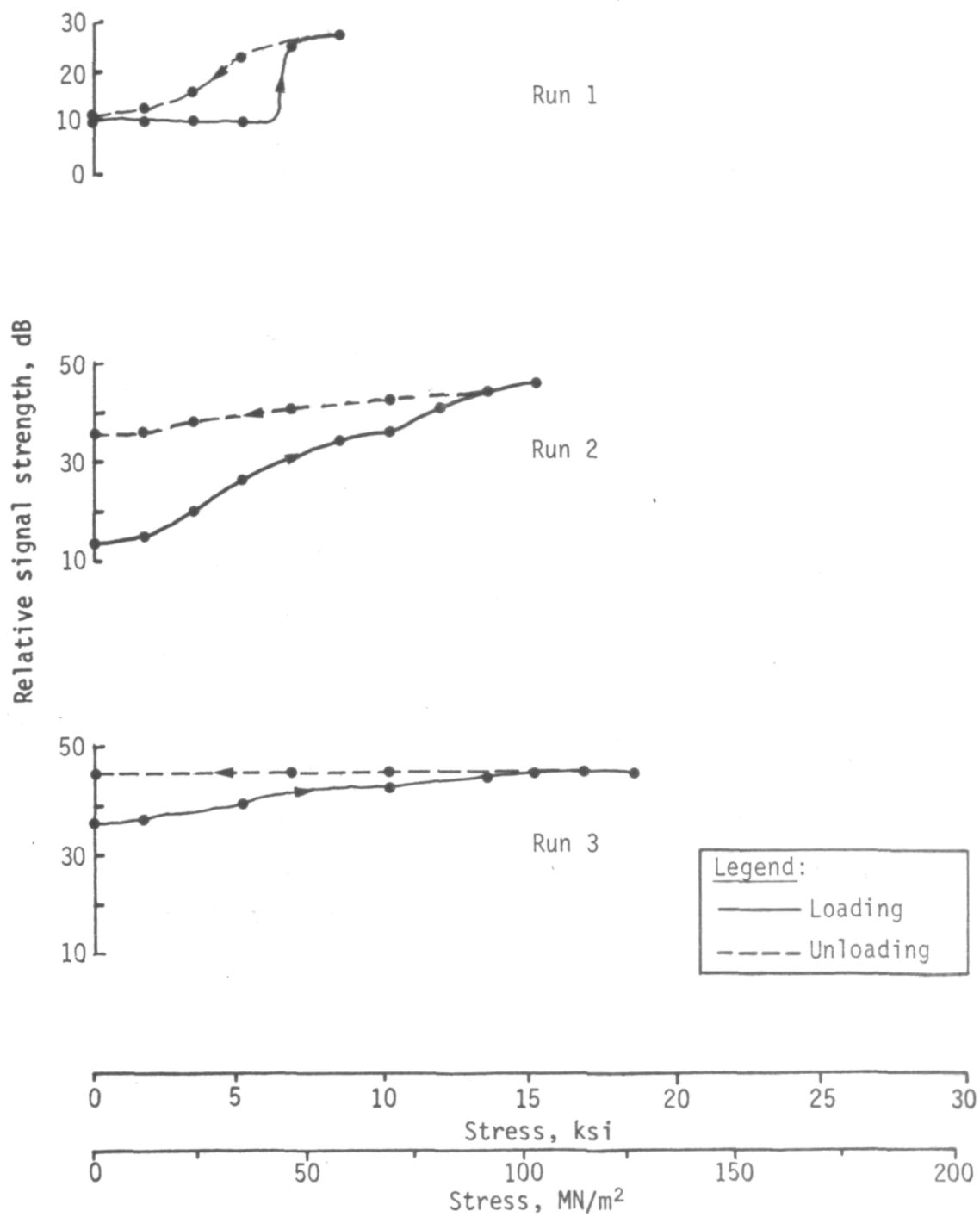


Figure 34. - Effect of loading on signal strength (specimen R-5).

evaluated. A comparison of nominal net stresses required to achieve full opening (as evidenced by no decrease in signal strength during unloading) for each specimen is given in the table below. The stresses were of the magnitude of the yield strength of welded 2219 aluminum.

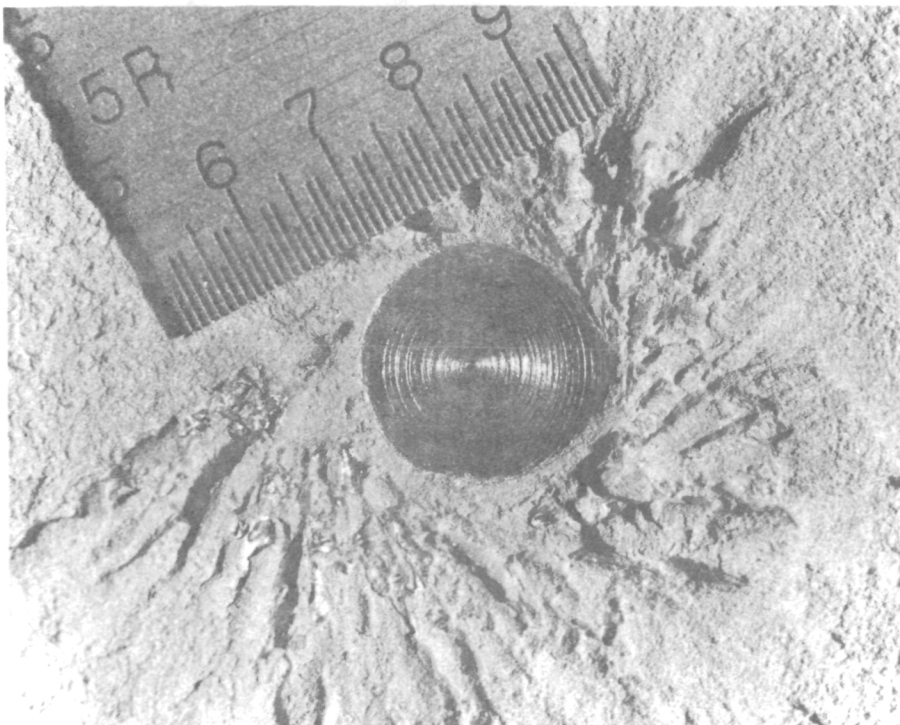
Specimen no.	Nominal defect dia,		Stress,	
	mm	(in.)	MN/m ²	(ksi)
R-1	4.8	(3/16)	128	(18.5)
R-2	6.4	(1/4)	139	(20.2)
R-3	7.9	(5/16)	126	(18.2)
R-4	9.5	(3/8)	139	(20.2)
R-5	11.1	(7/16)	116	(16.8)

After full residual crack opening of the lack-of-fusion defects, the five specimens were forwarded to Lewis Research Center for C-scan examination using the pulse-echo shear-wave technique. All defects were detectable. However, the C-scan was not capable of establishing the sizes of the defects.

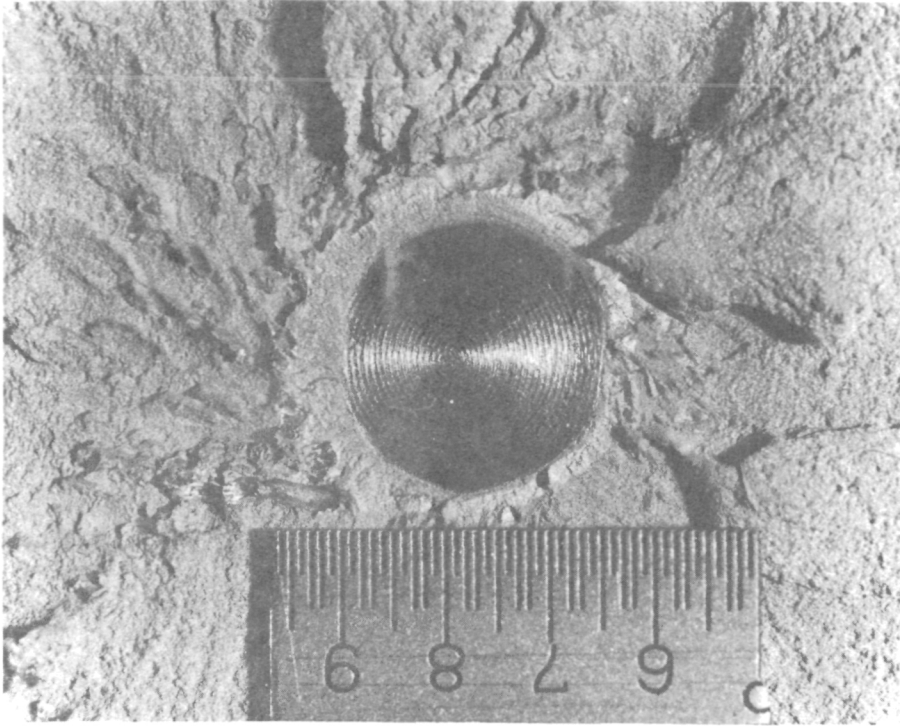
To obtain growth data after being C-scanned, the specimens were fatigue cycled and fractured to reveal the size of the defect. The diameter was determined by measuring the area of the crack on a high-magnification photograph using a polar planimeter, then calculating the average diameter represented by that area. Defects in specimens R-2, R-3, and R-4 agreed well with the desired size. Specimen R-1 contained an oversized defect, and R-5 too small a defect. Sizes were as follows.

Specimen no.	Desired size, dia,		Actual size, dia.	
	mm	in.	mm	in.
R-1	4.8	0.188	5.8	0.228
R-2	6.4	0.250	6.3	0.250
R-3	7.9	0.312	7.8	0.306
R-4	9.5	0.375	9.2	0.362
R-5	11.1	0.438	9.7	0.380

Figure 35 includes photographs of the fractured faces of the five specimens. Crack growth data are given in a later chapter.



R-1



R-2

Figure 35. - Photographs of fracture faces of cylindrical LFD specimens.

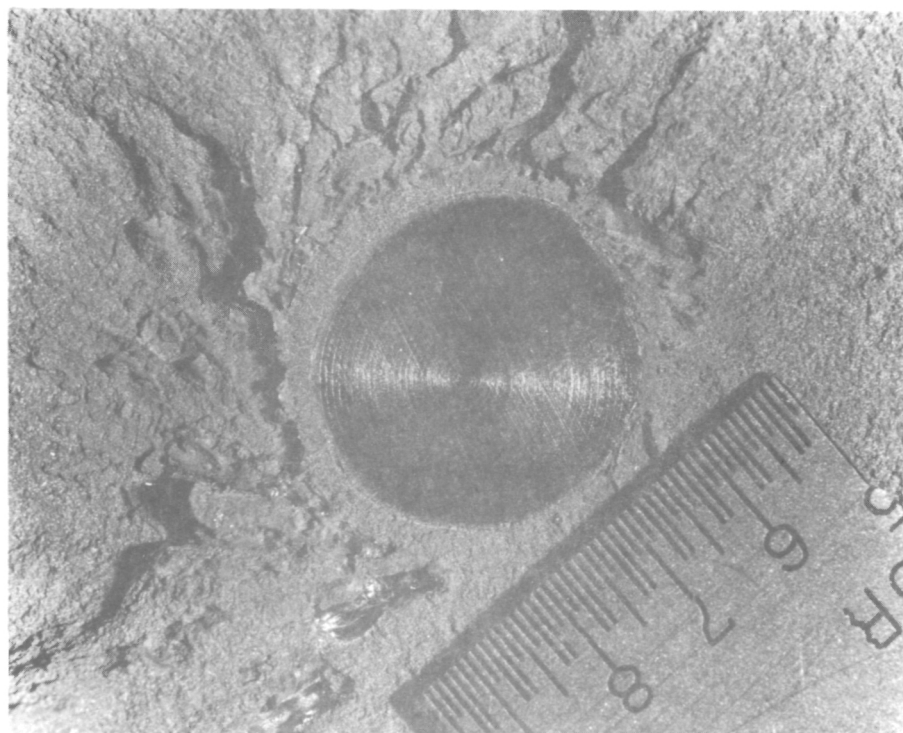
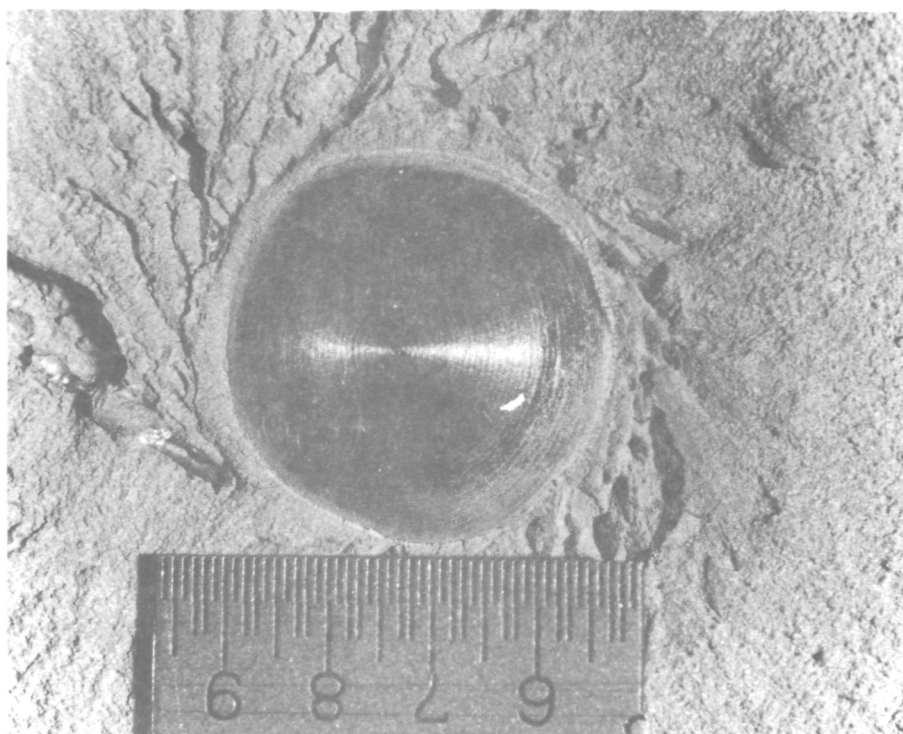
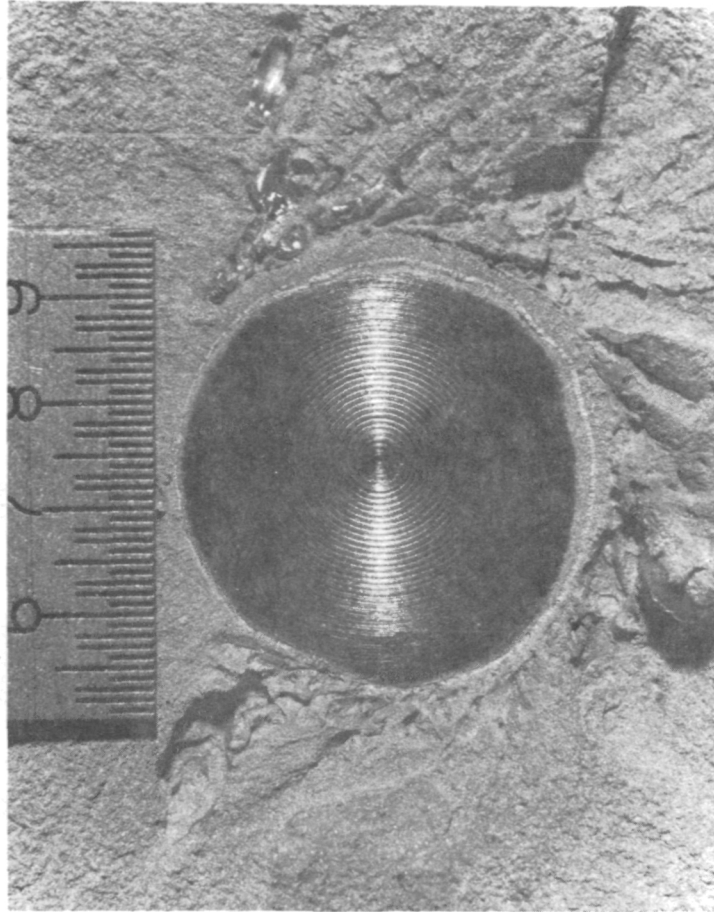


Figure 35. - Continued.



R-5

Figure 35. - Concluded.

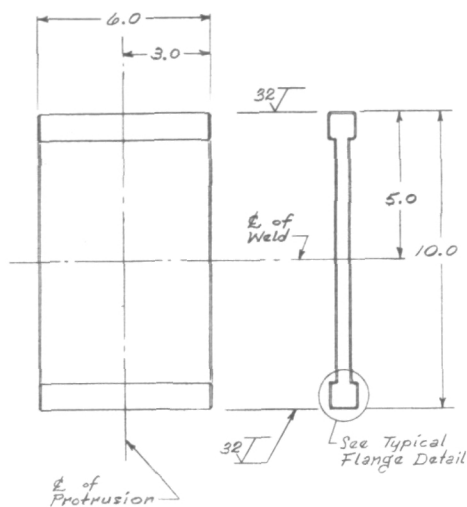
Flat Test Specimens

Specimen Preparation. - Flat test specimens were designed to incorporate a 1:5 elliptical lack-of-fusion defect. The technique used to obtain a buried elliptical defect was to machine the plate so that it was thicker in the region where the defect was to be. This thickening or surface projection served as a penetration inhibitor so that, although a constant depth of penetration was achieved, the resulting effect was to leave a lack-of-fusion area below the projection. To determine the proper contour for the projections, various geometries were studied.

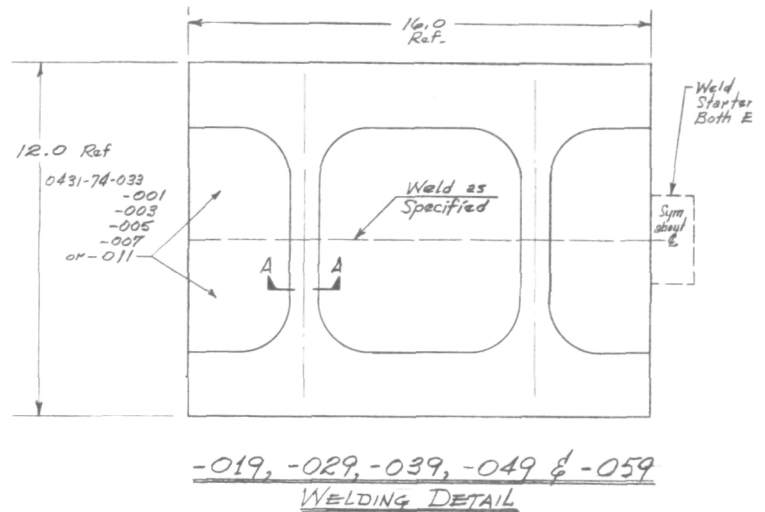
Initial attempts used the gas-tungsten-arc (GTA) welding process. Examination of the fractured faces revealed excessive porosity at the root of the first weld pass. Simultaneous development of flat weld specimens using the electron beam (EB) technique showed greater promise than the GTA technique. Therefore, development using the GTA process was discontinued. The principal problem

with the EB technique was development of weld parameters that would minimize "spiking" and fine root porosity. The Boeing Company was selected to prepare all flat-panel specimens. Sample specimens exhibited some dimensional inconsistency caused by beam spiking and fluctuations in the weld beam pattern, but were relatively good.

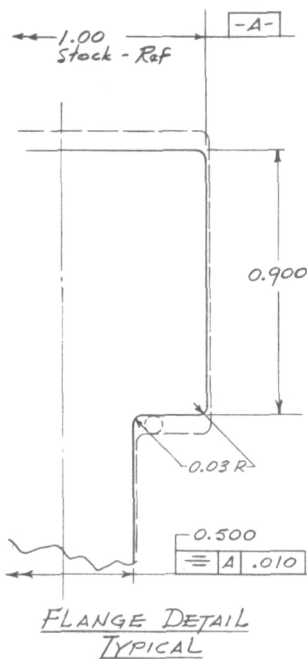
Figure 36 is a drawing of the flat weld specimen blank. Figure 37 is a drawing showing specifications for final machining. Figure 38 shows the gripping apparatus used for evaluation with the longitudinal-wave pulse-echo technique.



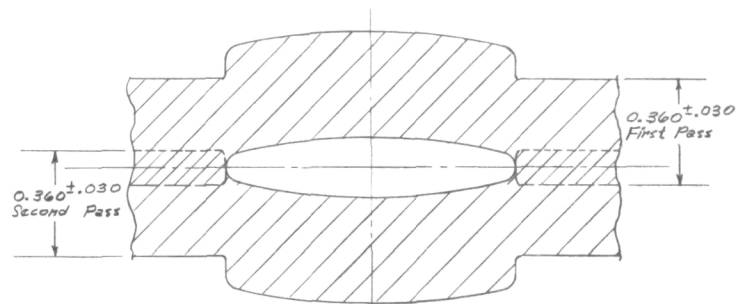
-019, -029, -039, -049, -059
MACHINING DETAIL



-019, -029, -039, -049 & -059
WELDING DETAIL



Note: Dimensions in inches



DESIRED FLAW SHAPE
SECTION A-A (TYPICAL) No Scale

- Weld Notes:
1. All Panels to be Welded Using Electron Beam Welding Process.
 2. Weld Starter Plates to be Tack Welded to Each End of the Weld Test Panels to Assure Tight Fit-up. Tack Welding to be Done before Placing the Panel into the EB Weld Chamber.
 3. Welding to be Done from both Sides. Both Weld Passes to Result in Controlled Penetration Depth of 0.360 ± 0.030 inches.
 4. Weld Beads to be Porosity-Free Particularly along the Elliptical Lack of Penetration within the Build-up Area of the Weld Bead. Maximum Single Porosity Size Not to Exceed 0.010 inch Diameter.
 5. Welding to be Done without Adding any Weld Wire to the Weld Bead.
 6. All Faying Surfaces to be Left in As-Machined Conditions.
 7. All Panels before Tack Welding are to be Cleaned Using Acetone Only. No Other Solvents are Permitted.
 8. All Faying Surfaces Are to be Closely Examined for Nicks and Gouges that would Inhibit Tight Fit-up of the Panels. Obtain Disposition for Damaged Parts from the Originating Engineer.
 9. All Test Panels to be Welded Using Identical Welding Procedure to Assure Dimensional Control of Lack of Fusion and Residual Stress Levels.

Figure 37. - Configuration of flat test specimen.

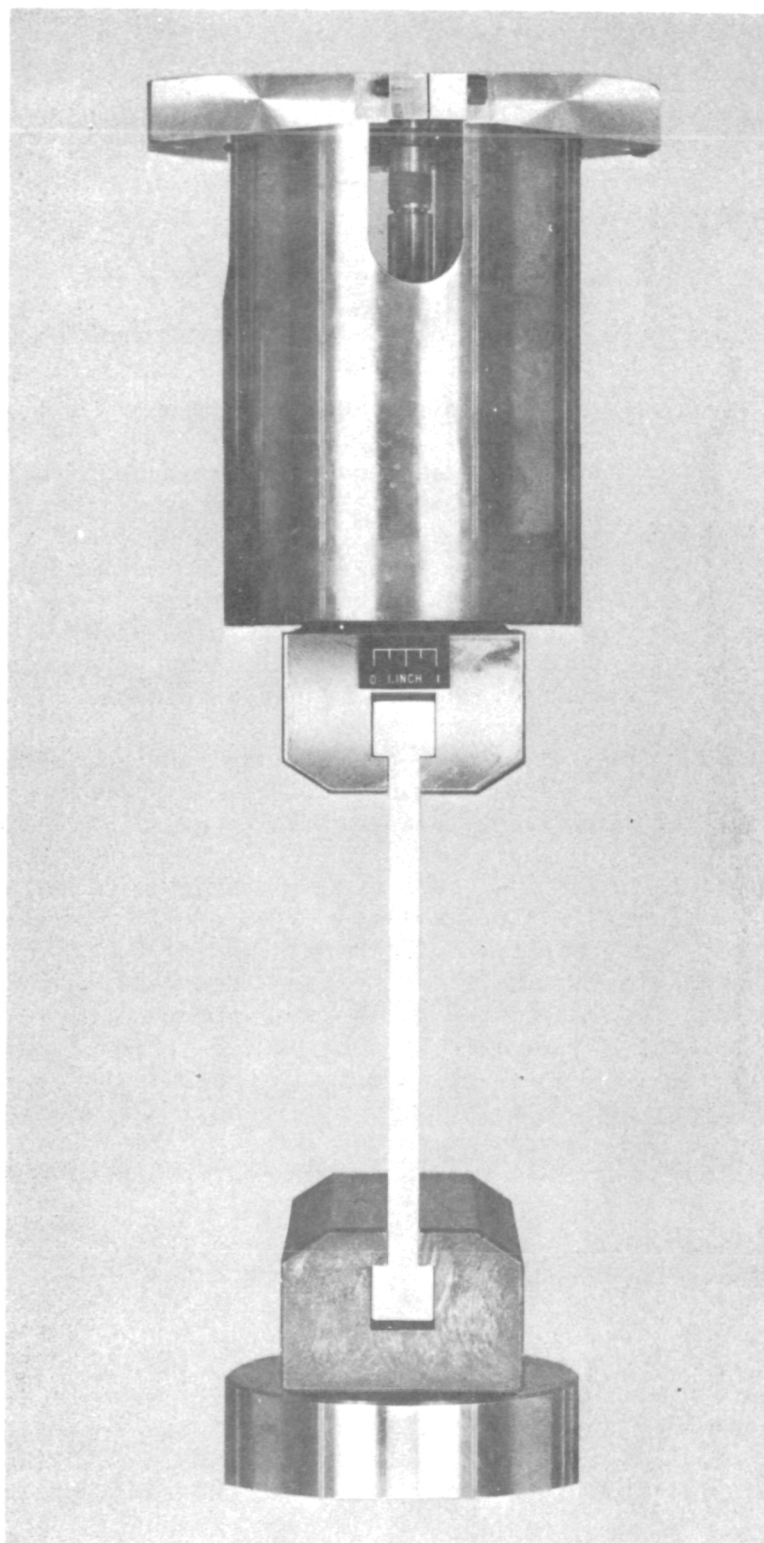


Figure 38. - Gripping system for flat specimens.

EFFECT OF LOADING CONDITIONS ON NONDESTRUCTIVE INSPECTION (NDI) SYSTEM RESPONSE TO LACK-OF-FUSION DEFECTS (LFD)

The objective of this part of the program was to establish the characteristics of the NDI system under controlled conditions of crack closure and crack geometry. Both cylindrical and flat specimens were evaluated.

The approach used was to investigate the effect of loading on the detection characteristics of round and flat specimens containing a variety of defects.

Cylindrical Test Specimens

Twelve cylindrical specimens were evaluated, including one that was welded so there was no lack-of-fusion defect. The ultrasonic technique was identical to that previously described. Only the longitudinal-wave pulse-echo technique was used. This group of specimens did not exhibit as tight a defect as found in evaluation of specimens prepared for preliminary testing. Therefore, the effect of compressive loading to simulate a tighter defect was evaluated for some of these specimens.

Based on the results of preliminary testing, data were available to facilitate selection of load levels. Therefore, fewer runs were required for each specimen.

Results showed that full crack opening occurred at stress levels from 46 MN/m^2 (6.7 ksi) to 93 MN/m^2 (13.5 ksi)--in all cases less than the 117 to 138 MN/m^2 (17 to 20 ksi) stress required to cause opening in the first series. Compressing the defect after full opening increased the stress required to achieve full opening on reloading. However, a compressive stress [$>200 \text{ MN/m}^2$ (30 ksi)] well into the plastic range was required to achieve a significant increase in the stress required to achieve full opening. Table IV summarizes the data for the cylindrical specimens evaluated in this task and compares results with data from preliminary tests.

At least one of each of the five nominal defect sizes was evaluated. The following paragraphs summarize the behavior for each defect size.

Three specimens of the smallest defect size [4.8 mm (3/16 in.) nominal size] were evaluated. Specimens R-7 and R-9 showed full opening at 81 MN/m^2 (12 ksi) and 70 MN/m^2 (10 ksi), respectively. Specimen R-14 opened at about the same stress level [70 MN/m^2 (10 ksi)]. The initial ultrasonic signal strength for specimen R-14 (24 dB) was lower than that for specimens R-7 and R-9 (32 and 35 dB, respectively), although all three required approximately the same stress to develop full crack opening.

TABLE IV. - SUMMARY OF CRACK OPENING
DATA FOR CYLINDRICAL SPECIMENS

Specimen no.	Group no.	Stress, MN/m ² (ksi)		
		Tensile stress required to achieve full residual crack opening	Compressive stress applied	Tensile stress required to achieve full opening after compressive load
R-1	1	127 (18.5)		
R-2	1	139 (20.2)		
R-3	1	125 (18.2)		
R-4	1	139 (20.2)		
R-5	1	116 (16.8)		
R-6	2	93.0 (13.5)		
R-7	2	81.3 (11.8)		
R-8	2	69.6 (10.1)		
R-9	2	69.6 (10.1)		
R-10	2	69.6 (10.1)	151 (21.9)	81.3 (11.8)
R-11	2	16.5 (8.1)	220 (32.0)	11.6 (16.8)
R-12	2	81.3 (11.8)	302 (43.8)	-- --
R-13	2	73.7 (10.7)	185 (26.9)	81.3 (11.8)
R-14	2	69.6 (10.1)	209 (30.3)	127 (18.5)
R-15	2	59.4 (8.6)	255 (37.0)	127 (18.5)
R-16	2	69.6 (10.1)	255 (37.0)	127 (18.5)

Specimen R-14 was then compressed at progressively increasing levels to a maximum stress of 208 MN/m² (30 ksi). The curve at the highest compressive stress was not flat, indicating that full closure did not occur. Reloading in tension required a stress of 116 MN/m² (17 ksi) to achieve full residual crack opening. Table V summarizes data for the three specimens. The table does not include all ultrasonic readings taken during loading and unloading, only the initial value before stressing, the value at maximum stress, and the final value after unloading. Figure 39 is a graphical presentation of the complete data.

The 6.4-mm (1/4-in.) nominal-sized defect was evaluated using two specimens (R-8 and R-15). Both exhibited an initial ultrasonic signal strength of approximately 37 dB. Specimen R-8 showed full crack opening after loading to 70 MN/m² (10 ksi). Specimen R-15 showed full opening after loading to 58 MN/m² (8 ksi). Specimen R-15 was then progressively loaded in compression to 255 MN/m² (37 ksi). Full crack closure appeared to occur at a stress of 209 MN/m² (30 ksi). Additional compressive loading runs resulted in an unloaded signal strength exceeding that at the start of the run. Full opening during tension reloading occurred at 127 MN/m² (18 ksi). Table VI and figure 40 summarize data for these specimens.

TABLE V. - EFFECT OF LOADING ON ULTRASONIC SIGNAL STRENGTH FOR
CYLINDRICAL SPECIMENS WITH 4.9-mm (3/16-in.) DEFECT

Specimen no.	Run no.	Initial signal strength at zero load, dB	Maximum load,		Maximum stress,		Signal strength at maximum load, dB	Final signal strength at zero load, dB
			kN	(kip)	MN/m ²	(ksi)		
R-7	1	32.3	156	(35)	81.3	(11.8)	33.7	33.7*
	2	33.8	222	(50)	116	(16.8)	33.8	34.3
R-9	1	35.1	133	(30)	69.6	(10.1)	37.5	37.0*
	2	37.1	311	(70)	174	(25.3)	40.0	40.6
R-14	1	24.5	44	(10)	23.4	(3.4)	25.2	24.9
	2	24.9	67	(15)	34.4	(5.0)	25.7	25.4
	3	25.4	89	(20)	46.2	(6.7)	26.2	25.7
	4	25.7	111	(25)	57.9	(8.4)	26.9	26.2
	5	26.2	133	(30)	69.6	(10.1)	27.5	27.4*
	6	27.4	156	(35)	116	(16.8)	28.3	28.2
	7	28.5	-67	(-15)	-34.4	(-5.0)	27.2	27.7
	8	27.7	-89	(-20)	-46.2	(-6.7)	28.7	27.7
	9	27.7	-111	(-25)	-57.9	(-8.4)	19.7	28.0
	10	28.0	-133	(-30)	-69.6	(-10.1)	15.7	27.4
	11	27.4	-178	(-40)	-92.3	(-13.4)	11.3	25.0
	12	25.0	-222	(-50)	-116	(-16.8)	10.0	21.0
	13	21.0	-267	(-60)	-139	(-20.2)	7.3	18.9
	14	18.7	-311	(-70)	-174	(-25.3)	2.5	16.5
	15	16.3	-356	(-80)	-185	(-26.9)	4.2	16.7
	16	16.5	-400	(-90)	-208	(-30.2)	8.0	16.9
	17	16.9	22	(5)	11.7	(1.7)	19.8	17.4
	18	17.4	44	(10)	23.4	(3.4)	25.7	17.8
	19	17.8	67	(15)	34.4	(5.0)	25.7	18.3
	20	18.3	89	(20)	46.2	(6.7)	28.9	19.3
	21	19.3	111	(25)	57.9	(8.4)	28.0	20.9
	22	20.7	133	(30)	69.6	(10.1)	28.9	21.8
	23	21.8	156	(35)	81.3	(11.8)	29.4	23.4
	24	23.4	178	(40)	92.3	(13.4)	29.7	25.4
	25	25.2	200	(45)	104	(15.1)	30.0	27.2
	26	27.2	222	(50)	116	(16.8)	30.0	29.4
	27	29.3	245	(55)	127	(18.5)	30.0	30.3*

* Full residual defect opening.

Two specimens (R-10 and R-13) of the 8-mm (5/16-in.) defect series were evaluated. Specimen R-10 exhibited an initial signal strength of 37 dB and full opening at a stress of 70 MN/m² (10 ksi). Specimen R-13 exhibited a lower initial signal (26 dB) but full opening at the same stress as R-10. Both specimens were subjected to compression loading. Specimen R-10 was loaded to 151 MN/m² (22 ksi). The curve of signal strength versus loading showed that complete closure did not occur. Reloading in tension produced full opening at a level [81 MN/m² (12 ksi)] only slightly greater than the initial loading exhibited. Specimen R-13 was loaded in compression to 185 MN/m² (27 ksi) and did not exhibit the flat curve suggesting full closure because the unloaded signal strength exceeded the initial value. Reloading in tension resulted in a modest increase in tensile stress required to achieve full opening compared to the initial loading cycle. Table VII and Figure 41 contain the data for specimens R-10 and R-13.

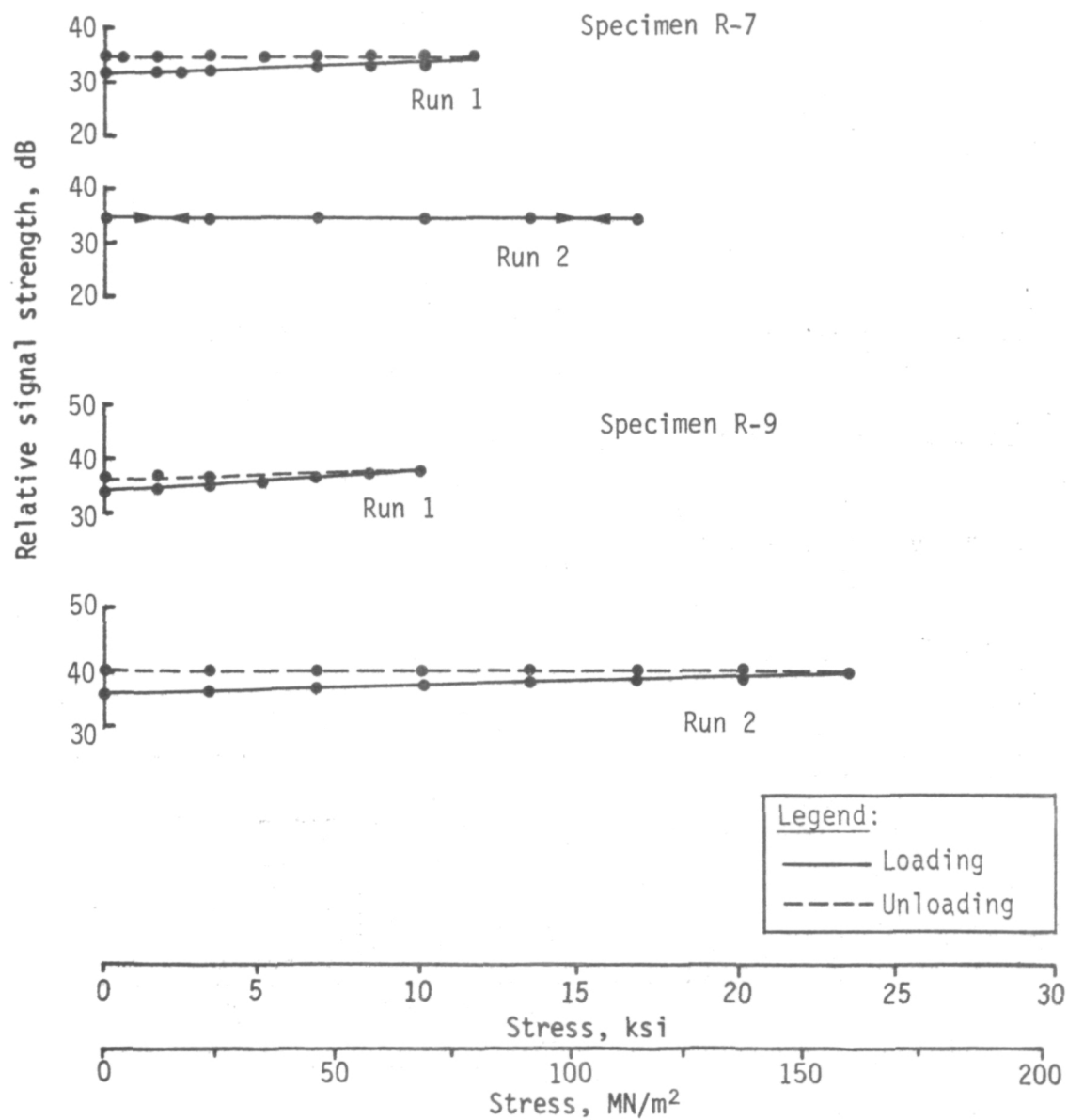


Figure 39. - Signal strength vs stress for cylindrical specimens with 4.8-mm (3/16-in.) defects.

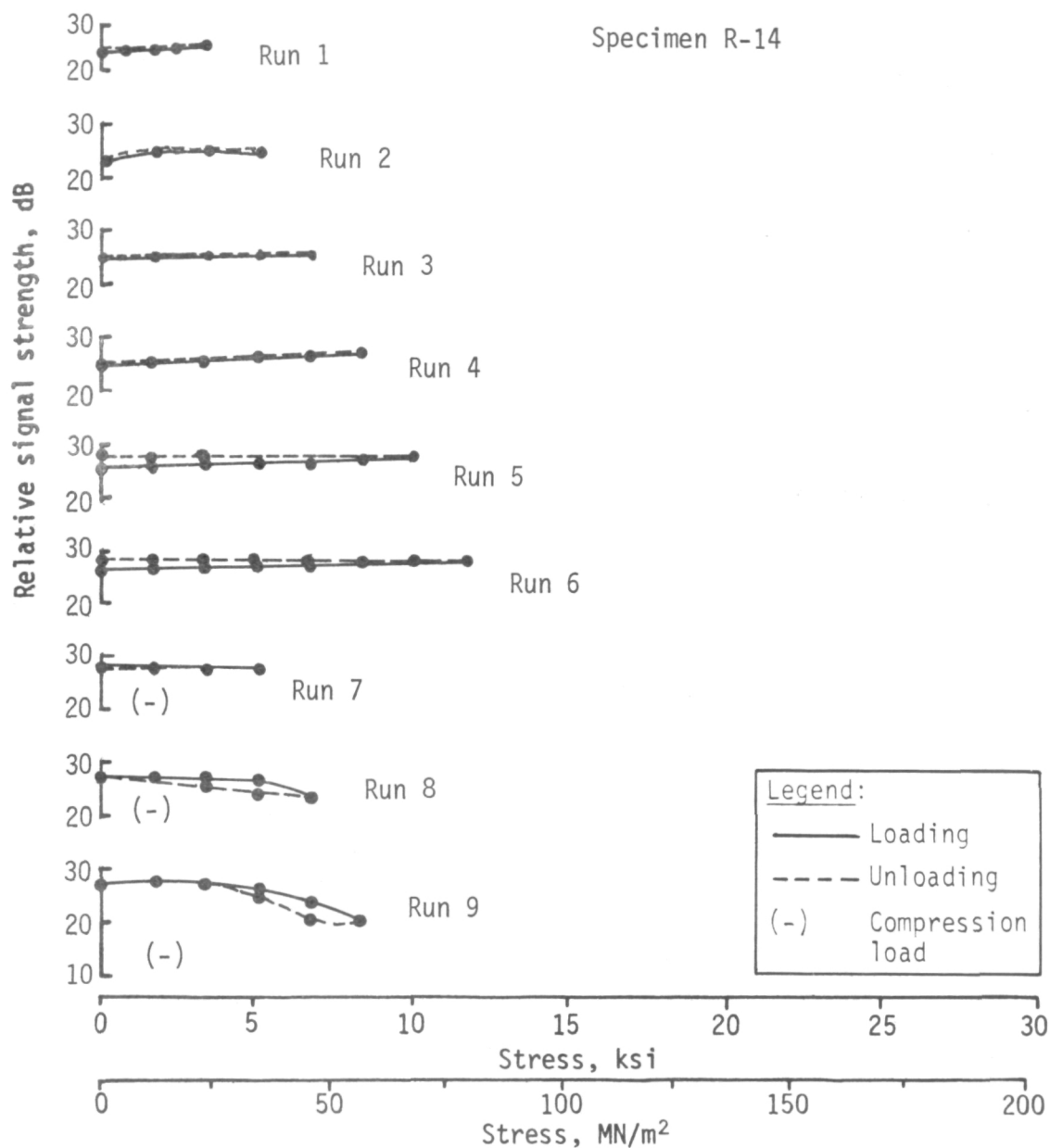


Figure 39. - Continued.

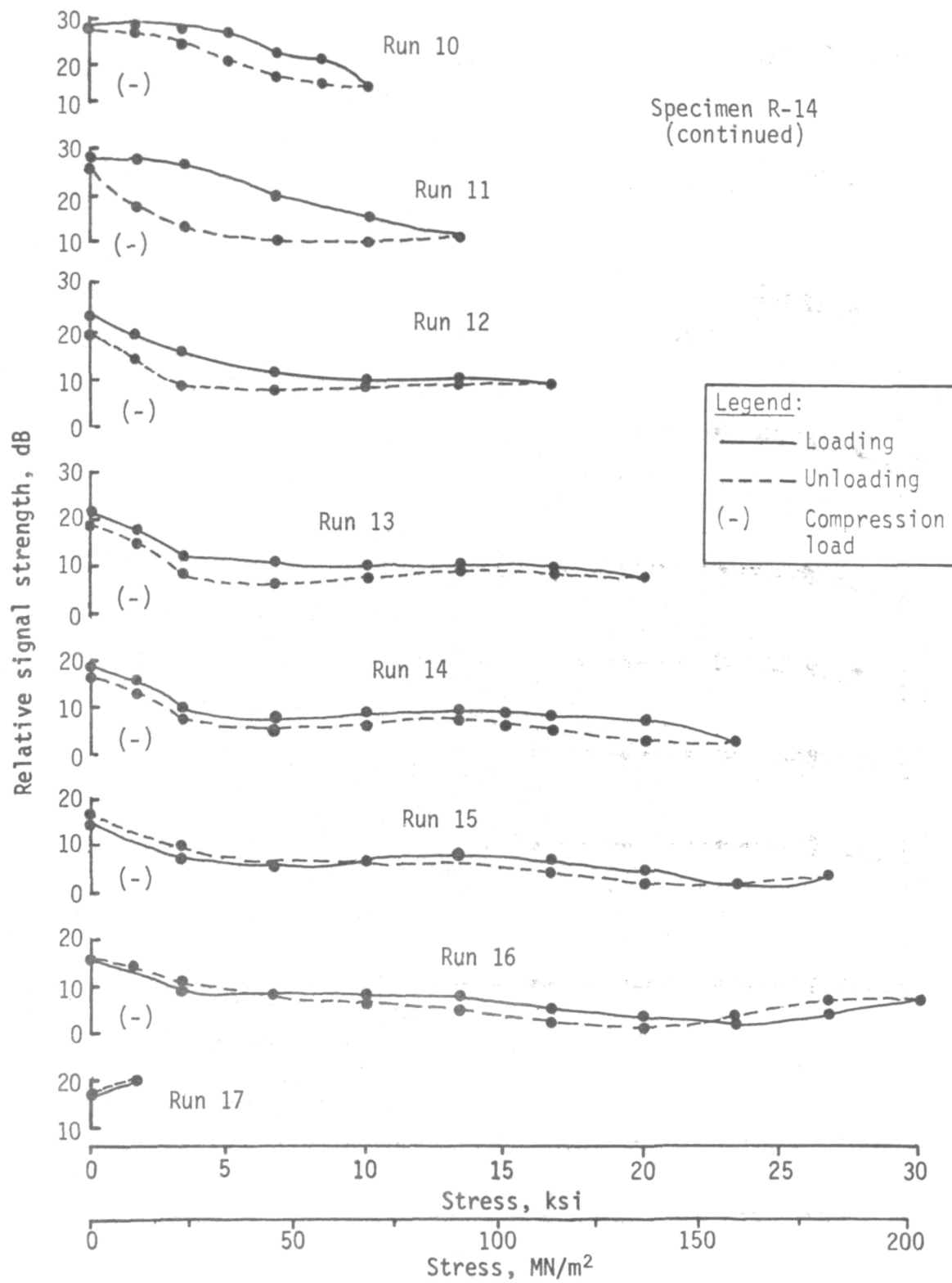


Figure 39. - Continued.

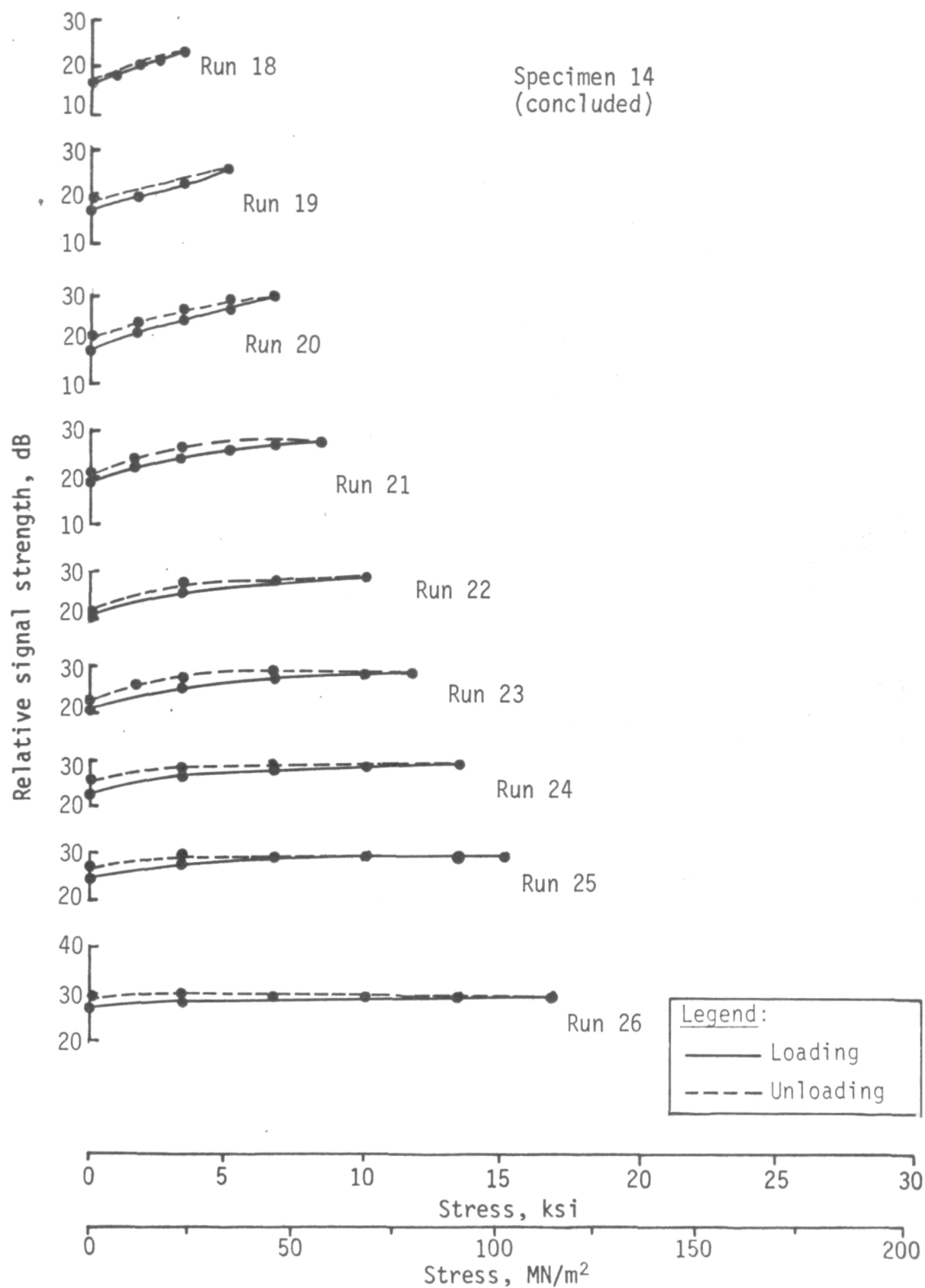


Figure 39. - Concluded.

TABLE VI. - EFFECT OF LOADING ON ULTRASONIC SIGNAL STRENGTH FOR
CYLINDRICAL SPECIMENS WITH 6.4-mm (1/4-in.) DEFECT

Specimen no.	Run no.	Initial signal strength at zero load, dB	Maximum load,		Maximum stress,		Signal strength at maximum load, dB	Final signal strength at zero load, dB
			kN	(kip)	MN/m ²	(ksi)		
R-8	1	36.5	133	(30)	69.6	(10.1)	39.2	39.0*
	2	39.0	391	(88)	204	(29.6)	46.0	Failed at max load
R-15	1	37.0	44	(10)	23.4	(3.4)	39.0	37.1
	2	37.1	67	(15)	34.4	(5.0)	39.4	38.2
	3	38.2	89	(20)	46.2	(6.7)	39.4	39.2
	4	39.2	111	(25)	57.9	(8.4)	39.8	39.7*
	5	39.7	133	(30)	69.6	(10.1)	40.3	40.3
	6	40.3	156	(35)	81.3	(11.8)	41.0	41.4
	7	41.4	-111	(-25)	-57.9	(-8.4)	36.9	41.0
	8	41.0	-133	(-30)	-69.6	(-10.1)	30.2	41.0
	9	41.0	-178	(-40)	-93.0	(-13.5)	18.3	40.0
	10	40.0	-222	(-50)	-116	(-16.8)	13.4	38.2
	11	38.2	-267	(-60)	-139	(-20.2)	13.5	26.3
	12	26.2	-311	(-70)	-163	(-23.6)	11.5	12.3
	13	16.3	-356	(-80)	-185	(-26.9)	10.7	13.7
	14	13.5	-400	(-90)	-209	(-30.3)	11.4	13.7
	15	13.7	-445	(-100)	-232	(-33.7)	10.3	14.0
	16	15.5	-489	(-110)	-255	(-37.0)	10.7	24.3
	17	23.8	44	(10)	23.4	(3.4)	37.0	26.2
	18	26.2	67	(15)	34.4	(5.0)	38.9	26.7
	19	26.2	89	(20)	46.2	(6.7)	39.4	27.0
	20	27.0	111	(25)	57.9	(8.4)	39.7	28.0
	21	28.0	133	(30)	69.6	(10.1)	40.2	29.2
	22	29.0	156	(35)	81.3	(11.8)	40.3	31.0
	23	30.7	178	(40)	93.0	(13.5)	40.7	33.3
	24	33.3	200	(45)	105	(15.2)	40.7	35.8
	25	35.8	222	(50)	116	(16.8)	40.9	38.2
	26	38.2	245	(55)	127	(18.5)	40.9	40.2*
	27	40.2	267	(60)	139	(20.2)	40.7	41.4
* Full residual defect opening.								

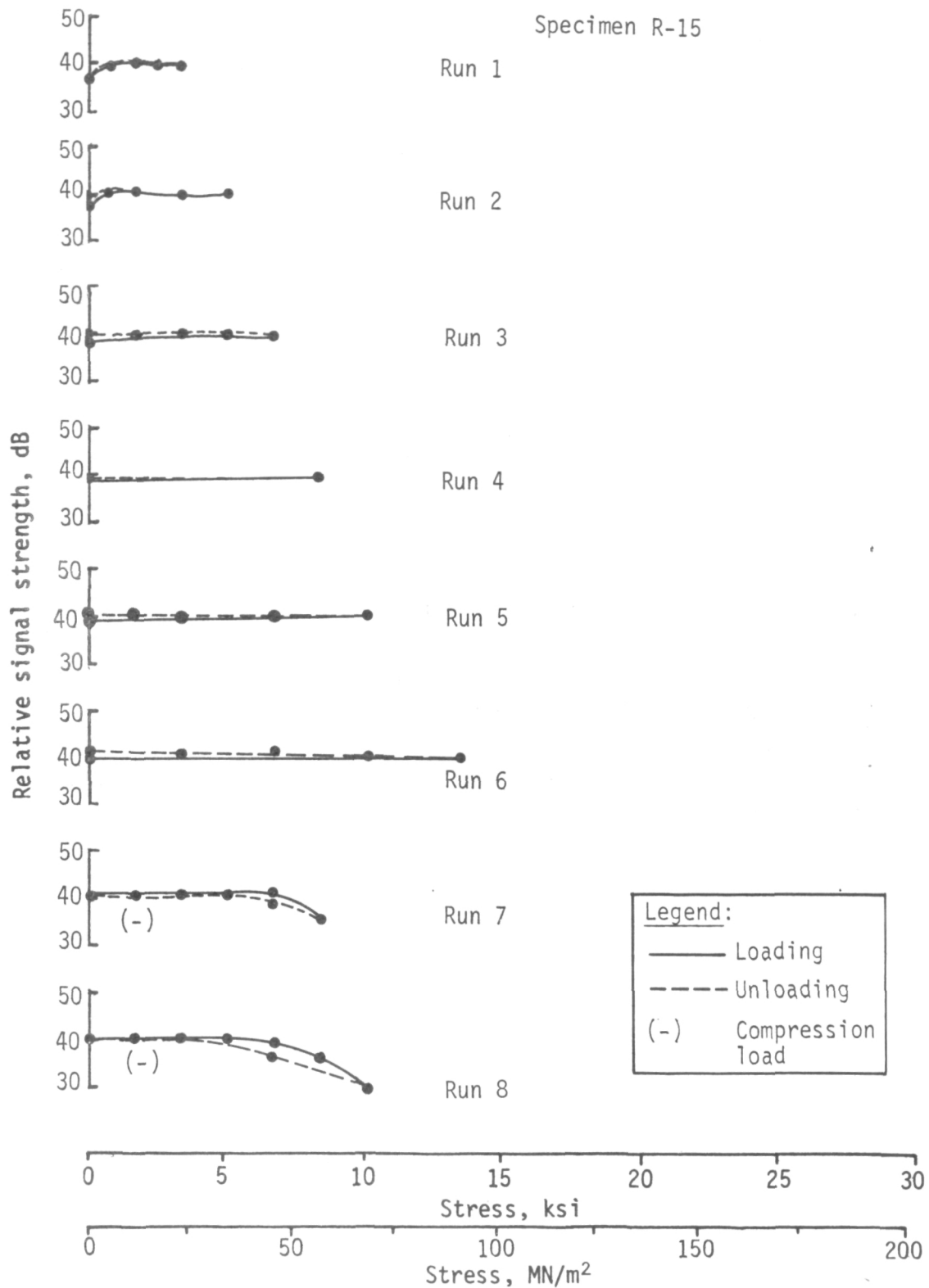


Figure 40. - Signal strength vs stress for cylindrical specimens with 6.4-mm (1/4-in.) defects.

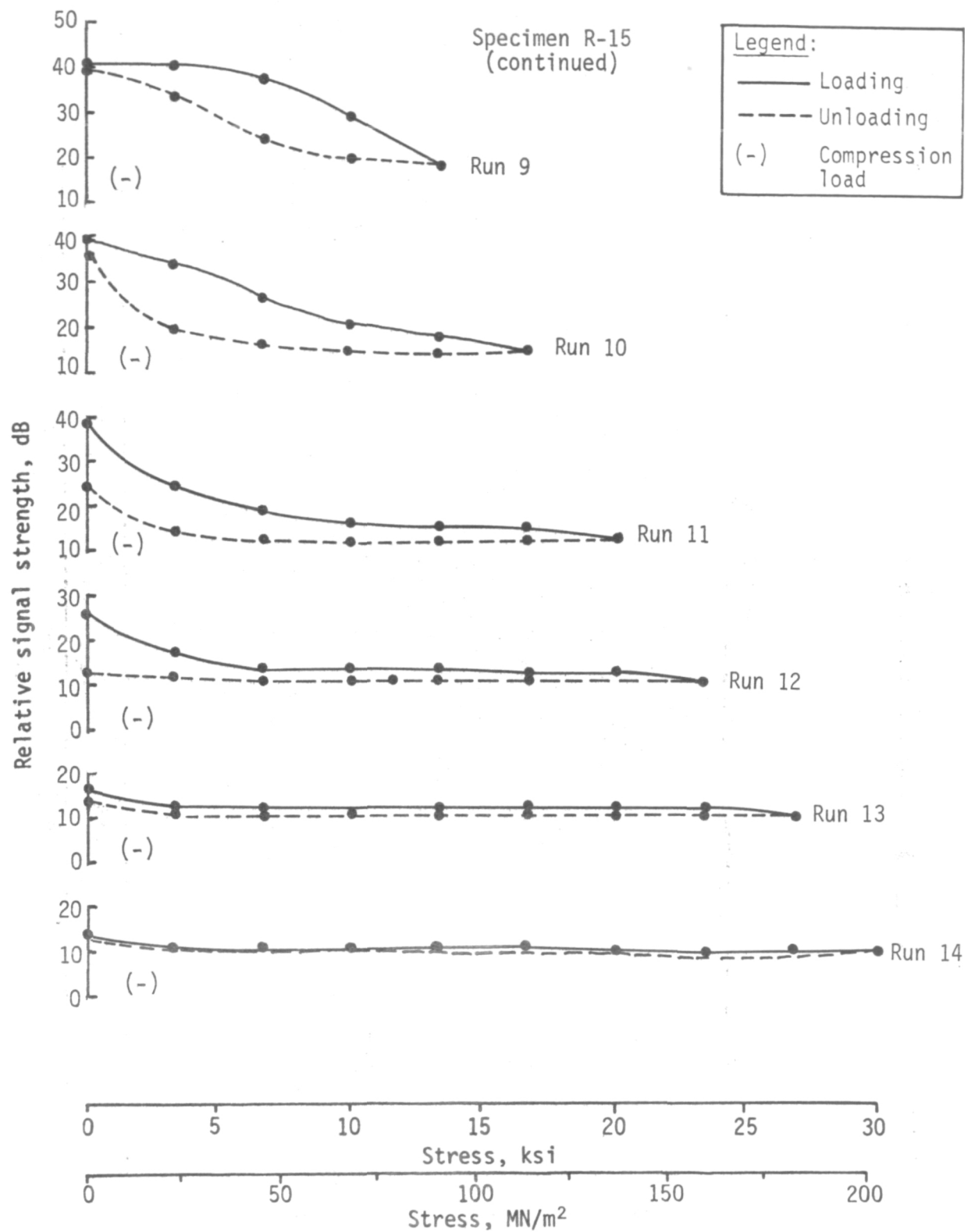


Figure 40. - Continued.

Specimen R-15
(continued)

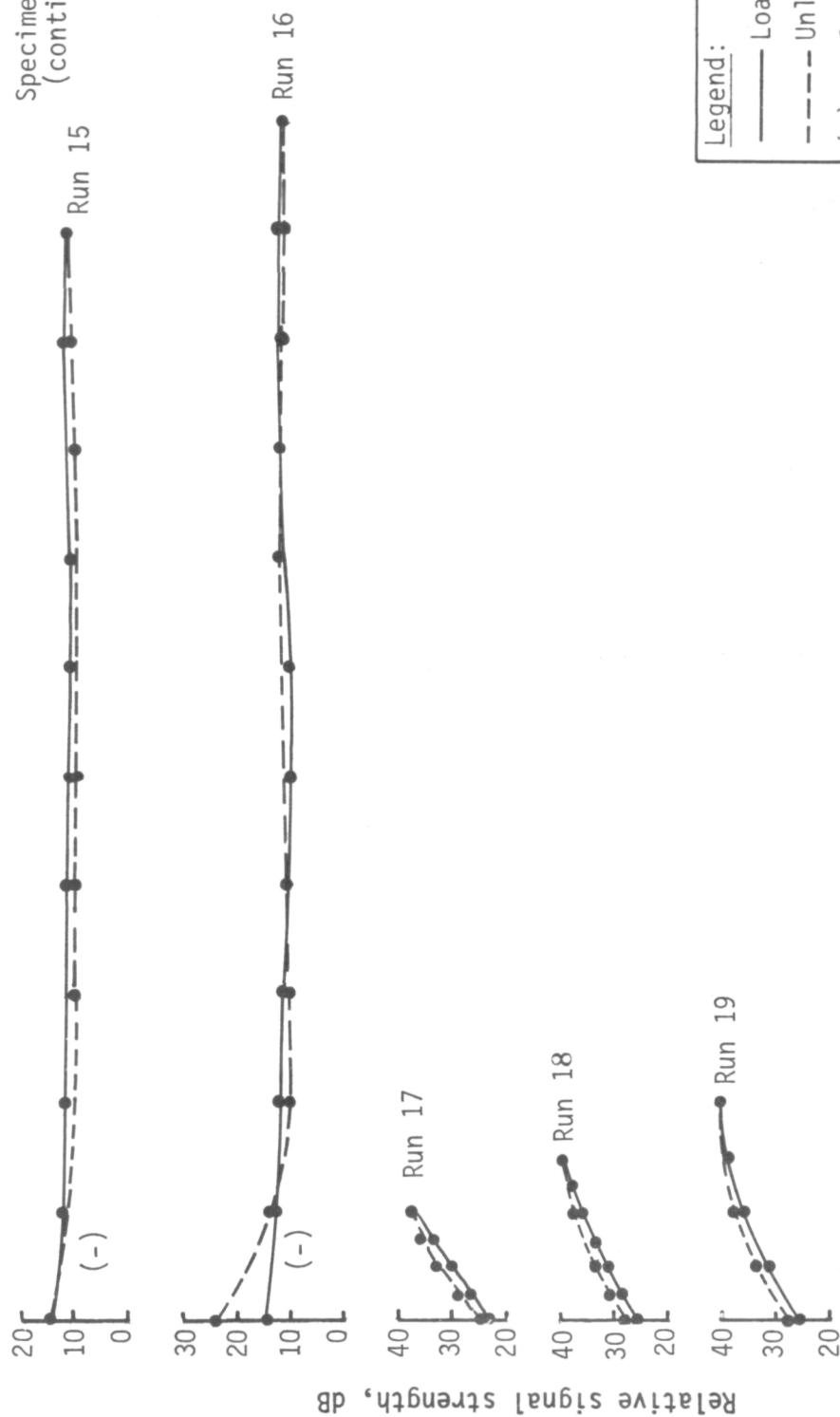


Figure 40. - Continued

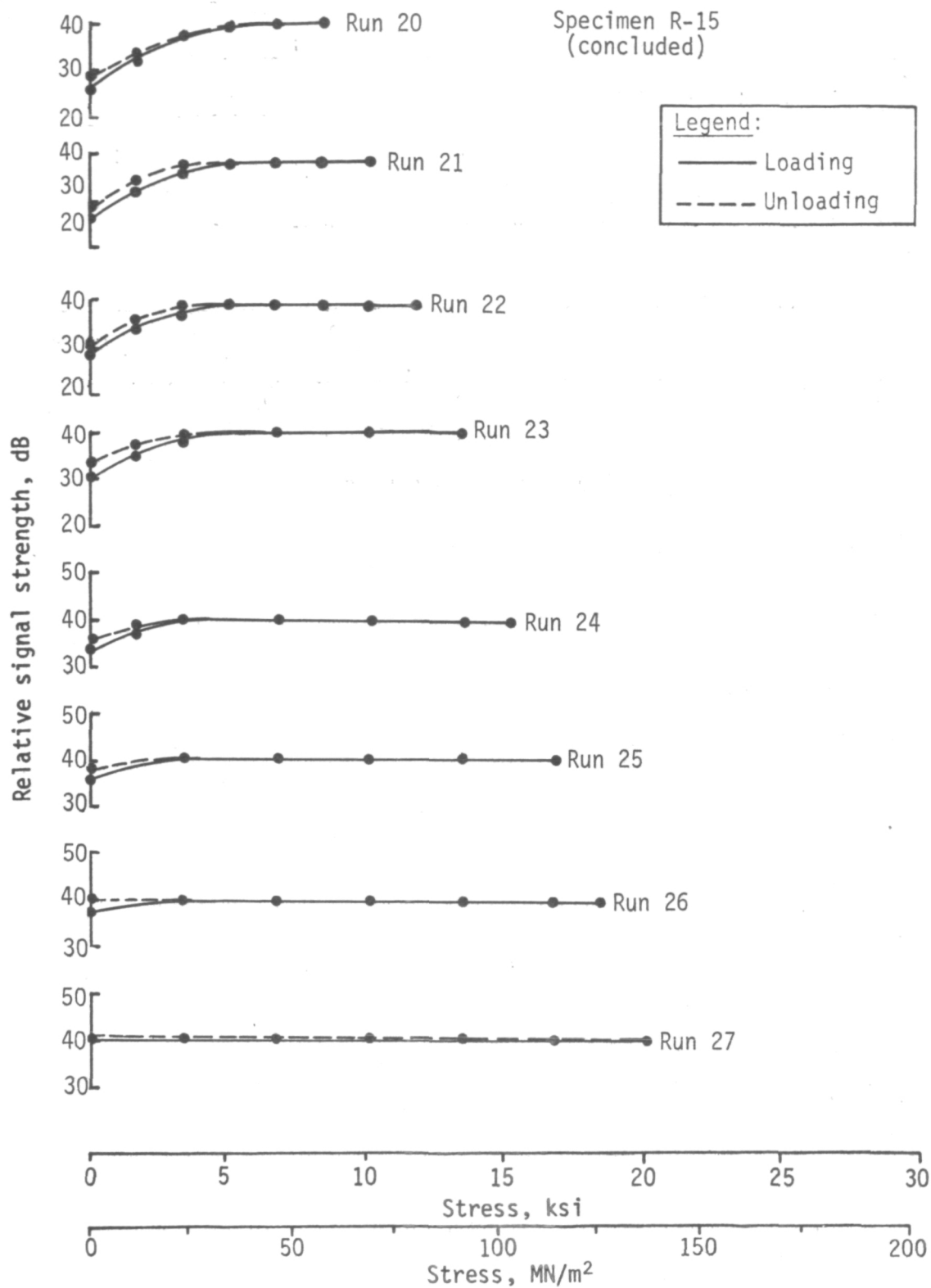


Figure 40. - Continued.

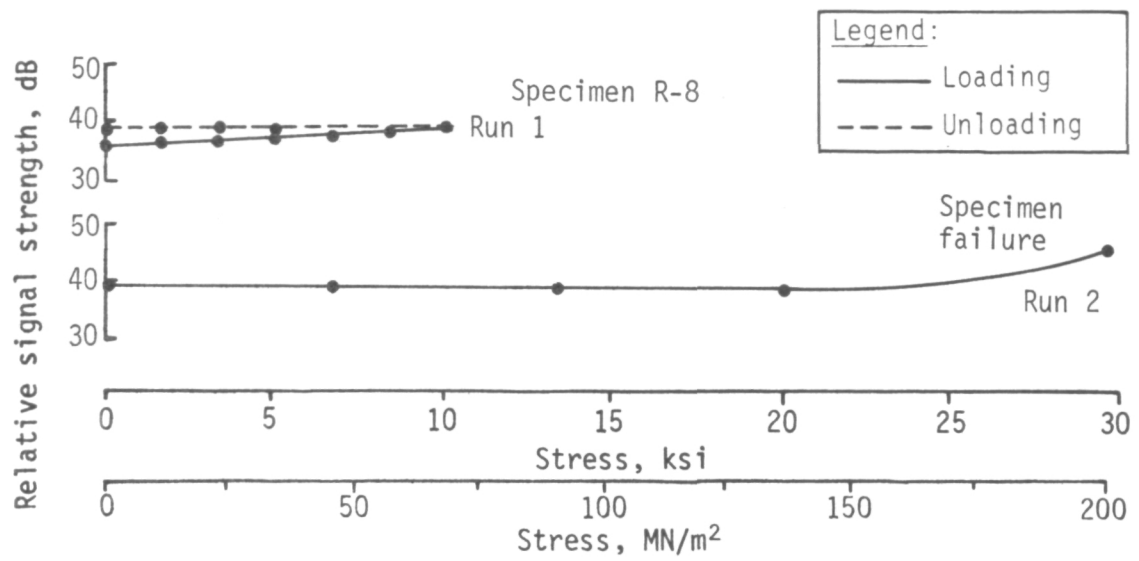


Figure 40. - Concluded.

TABLE VII. - EFFECT OF LOADING ON ULTRASONIC SIGNAL STRENGTH FOR
CYLINDRICAL SPECIMENS WITH 8-mm (5/16-in.) DEFECT

Specimen no.	Run no.	Initial signal strength at zero load, dB	Maximum load,		Maximum stress,		Signal strength at maximum load, dB	Final signal strength at zero load, dB
			kN	(kip)	MN/m ²	(ksi)		
R-10	1	37.0	89	(20)	46.2	(6.7)	44.8	41.8
	2	41.7	133	(30)	69.6	(10.1)	45.2	45.2*
	3	45.7	-289	(-65)	-151	(-21.9)	11.1	20.0
	4	19.0	44	(10)	23.4	(3.4)	44.2	25.8
	5	24.7	111	(25)	57.9	(8.4)	46.5	40.5
	6	39.7	156	(35)	81.3	(11.8)	46.9	46.7*
R-13	1	27.0	33	(7.5)	17.4	(2.5)	38.3	27.5
	2	27.5	44	(10)	23.4	(3.4)	38.5	28.5
	3	28.5	67	(15)	34.4	(5.0)	38.7	29.3
	4	29.3	89	(20)	46.2	(6.7)	39.0	31.2
	5	31.0	111	(25)	57.9	(8.4)	39.4	34.5
	6	34.5	133	(30)	69.6	(10.1)	39.5	38.9*
	7	38.9	-67	(-15)	-34.4	(-5.0)	20.5	37.5
	8	37.5	-89	(-20)	-46.2	(-6.7)	17.2	36.7
	9	36.7	-111	(-25)	-57.9	(-8.4)	14.2	34.7
	10	34.7	-133	(-30)	-69.6	(-10.1)	11.5	30.9
	11	30.9	-178	(-40)	-93.0	(-13.5)	7.0	16.2
	12	16.3	-222	(-50)	-116	(-16.8)	6.0	16.0
	13	16.0	-267	(-60)	-139	(-20.2)	7.8	15.8
	14	15.7	-311	(-70)	-163	(-23.6)	8.2	11.7
	15	11.7	-356	(-80)	-185	(-26.9)	8.9	26.0
	16	25.1	22	(5)	11.7	(1.7)	36.3	27.7
	17	27.7	44	(10)	23.4	(3.4)	39.5	29.2
	18	29.2	67	(15)	34.4	(5.0)	41.2	30.2
	19	30.2	89	(20)	46.2	(6.7)	40.9	31.7
	20	31.7	111	(25)	57.9	(8.4)	41.4	34.2
	21	34.2	133	(30)	69.6	(10.1)	41.5	37.5
	22	37.5	156	(35)	81.3	(11.8)	41.5	40.0
	23	40.0	178	(40)	93.0	(13.5)	41.8	41.5*
* Full residual defect opening.								

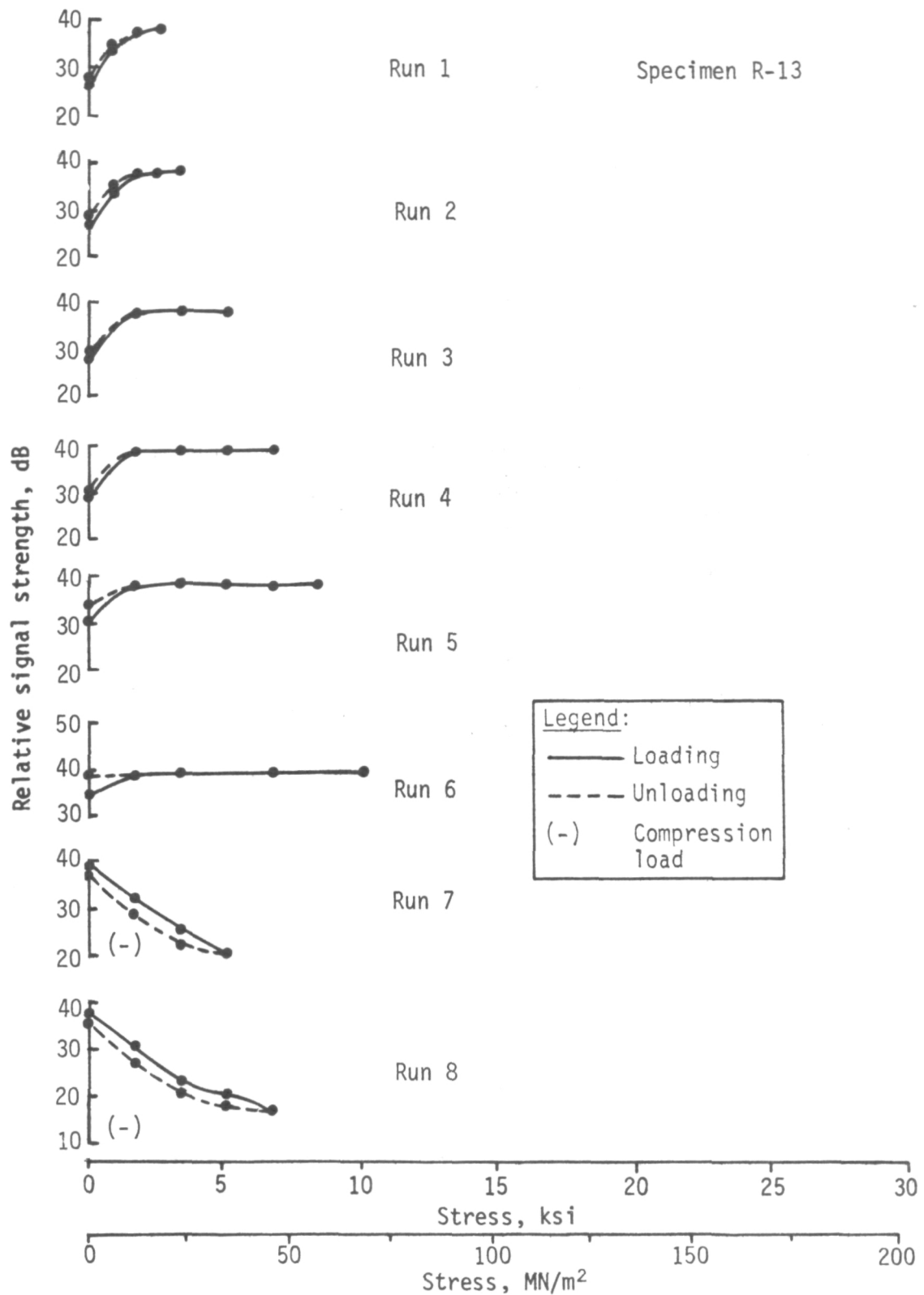


Figure 41. - Signal strength vs stress for cylindrical specimen with 8-mm (5/16-in.) defect.

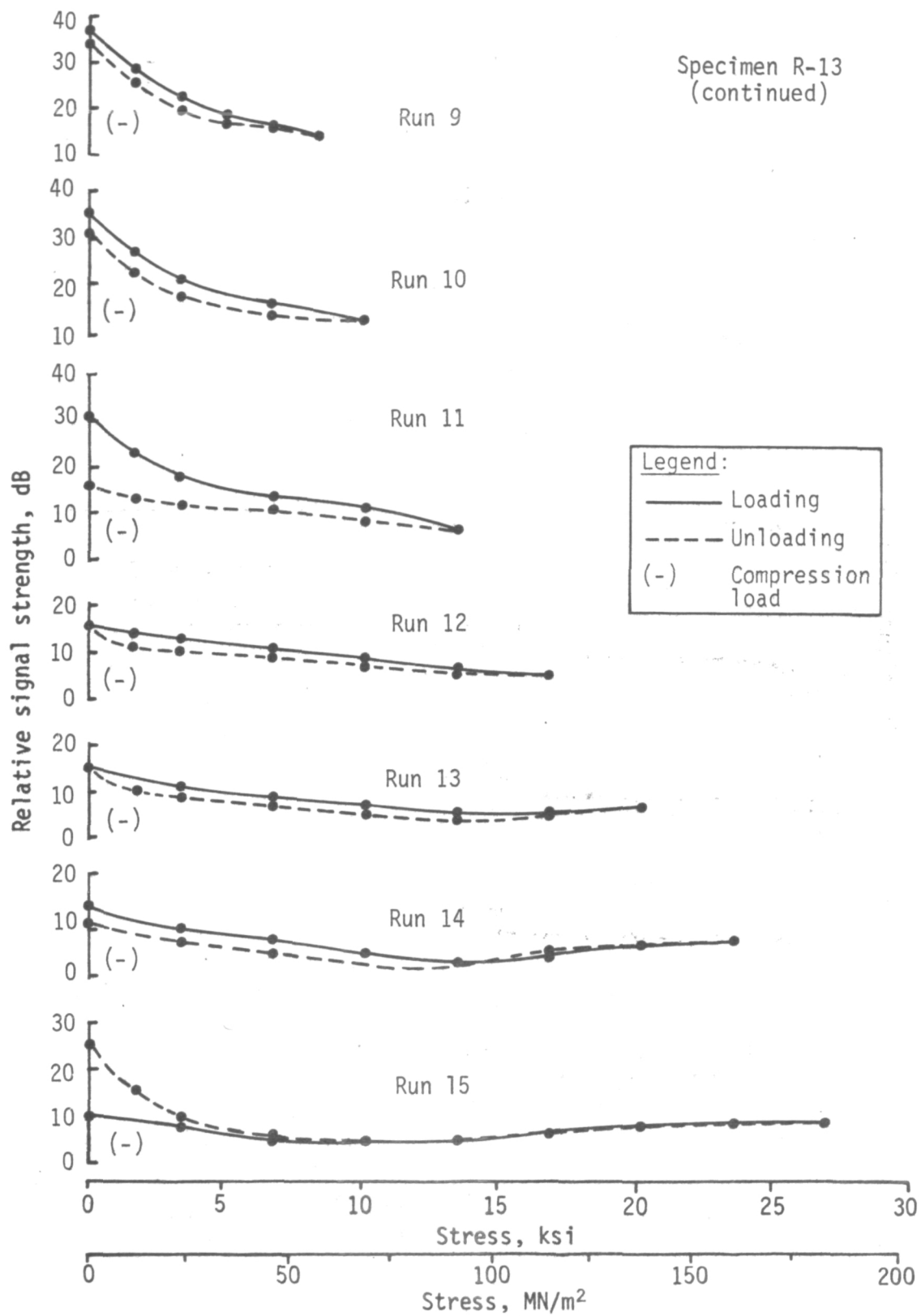


Figure 41. - Continued.

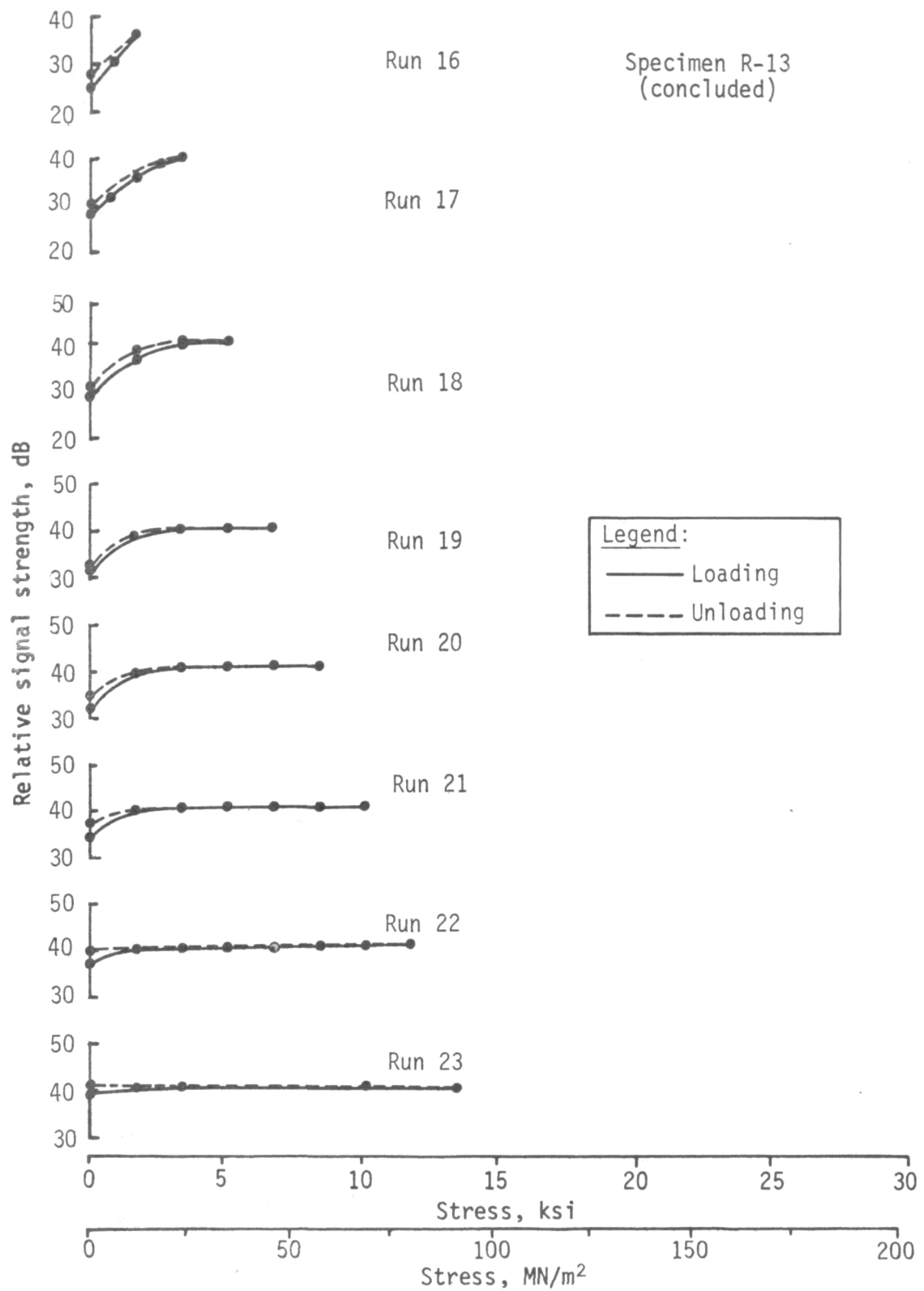


Figure 41. - Continued.

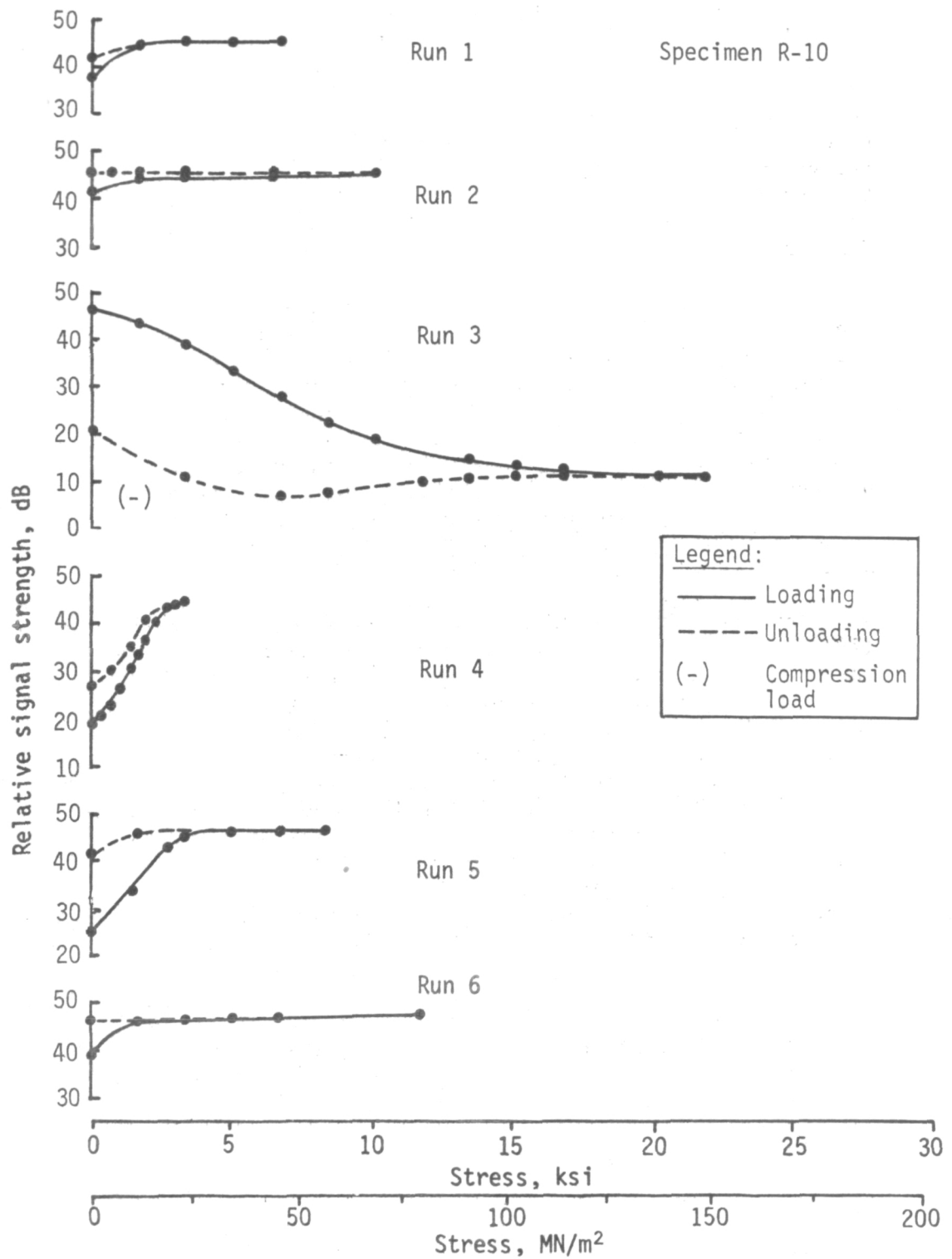


Figure 41. - Concluded.

A third specimen, R-17, with the same nominal size as R-10 and R-13 was prepared by the welding technique used for the first series of welded specimens. R-17 was evaluated to determine whether the initial signal level would indicate a tighter crack than found for specimens from the second series. Initial signal strength (24 dB) was approximately equal to the lower bound of the second series. The specimen was not loaded to full opening, but merely given a small tensile load [23 MN/m^2 (3 ksi)], then compressed to 139 MN/m^2 (20 ksi). The unloading curve was very flat and at approximately 9 dB, indicating a very tight flaw.

A single 9.5-mm (3/8-in.) defect specimen (R-11) was examined. This specimen exhibited a high initial ultrasonic reading (45 dB), suggesting a defect much less tight than the others. As anticipated, full residual defect opening occurred at a low stress [46 MN/m^2 (7 ksi)]. Compression loading to 200 MN/m^2 (32 ksi) did not achieve full defect closure but was sufficient to require a tensile stress for full opening more than twice that necessary to achieve initial opening. The stress level 116 MN/m^2 (17 ksi) was approaching the weld-joint yield strength. Table VIII summarizes data for this test, and figure 42 gives the data in graphic form.

Three specimens of the largest nominal defect size [11 mm (7/16 in.)] were evaluated. Specimen R-6 exhibited the lowest initial signal strength (20 dB) and required the highest stress of the second series of specimens [93 MN/m^2 (14 ksi)] to achieve full opening. Specimens R-12 and R-16 were much less tight and exhibited initial ultrasonic strength levels of 43 and 41 dB, respectively. Specimen R-12 exhibited full opening at 81 MN/m^2 (12 ksi) and R-16 at 70 MN/m^2 (10 ksi). Specimen R-12 was loaded to the highest compression level of all the second series specimens [302 MN/m^2 (44 ksi)]. This specimen did not exhibit complete closure. The signal strength of the unloaded specimen was greater than the initial value. The specimen showed visible evidence of bulging in the vicinity of the welded joint. No attempt was made to reload in tension.

Specimen R-16 was compressed to 255 MN/m^2 (37 ksi) and exhibited a fully flat curve of signal strength versus load. Subsequent tension loading caused full opening at 127 MN/m^2 (18 ksi). Table IX summarizes data for specimens R-6, R-12, and R-16, and figure 43 shows the data graphically.

A fully welded specimen (no buried defect) was evaluated by loading to 166 MN/m^2 (17 ksi) first in tension, then in compression. Both curves were quite flat and at a low signal strength (10 dB) (fig. 44).

TABLE VIII. - EFFECT OF LOADING ON ULTRASONIC SIGNAL STRENGTH FOR
CYLINDRICAL SPECIMEN WITH 9.5-mm (3/8-in.) DEFECT

Specimen no.	Run no.	Initial signal strength at zero load, dB	Maximum load,		Maximum stress,		Signal strength at maximum load, dB	Final signal strength at zero load, dB
			kN	(kip)	MN/m ²	(ksi)		
R-11	1	45.3	27	(6)	13.8	(2.0)	48.0	45.5
	2	47.1	36	(8)	18.6	(2.7)	48.0	45.7
	3	48.0	55	(12)	27.6	(4.0)	48.0	46.0
	4	46.0	71	(16)	37.2	(5.4)	48.1	46.5
	5	46.5	89	(20)	46.2	(6.7)	48.2	47.3
	6	47.3	107	(24)	55.9	(8.1)	48.4	48.3*
	7	47.3	-27	(-6)	-13.8	(-2.0)	43.7	47.7
	8	46.3	-44	(-10)	-23.4	(-3.4)	40.7	47.0
	9	47.0	-67	(-15)	-34.4	(-5.0)	36.9	47.7
	10	47.5	-89	(-20)	-46.2	(-6.7)	33.3	47.3
	11	47.3	-133	(-30)	-69.6	(-10.1)	27.0	44.9
	12	44.9	-267	(-60)	-139	(-20.2)	16.2	24.5
	13	25.0	-311	(-70)	-103	(-23.6)	15.5	21.5
	14	21.7	-423	(-95)	-220	(-32.0)	10.7	16.7
	15	16.7	27	(6)	13.8	(2.0)	25.2	18.0
	16	18.0	44	(10)	23.4	(3.4)	34.2	19.7
	17	19.3	67	(15)	34.4	(5.0)	46.2	22.7
	18	22.3	89	(20)	46.2	(6.7)	48.5	24.2
	19	24.2	111	(25)	57.9	(8.4)	48.9	26.2
	20	23.8	133	(30)	69.6	(10.1)	49.0	28.2
	21	28.2	156	(35)	81.3	(11.8)	49.0	32.2
	22	32.0	178	(40)	93.0	(13.5)	49.0	38.0
	23	37.3	200	(45)	105	(15.2)	49.2	45.1
	24	45.1	222	(50)	116	(16.8)	49.3	49.8*

* Full residual defect opening.

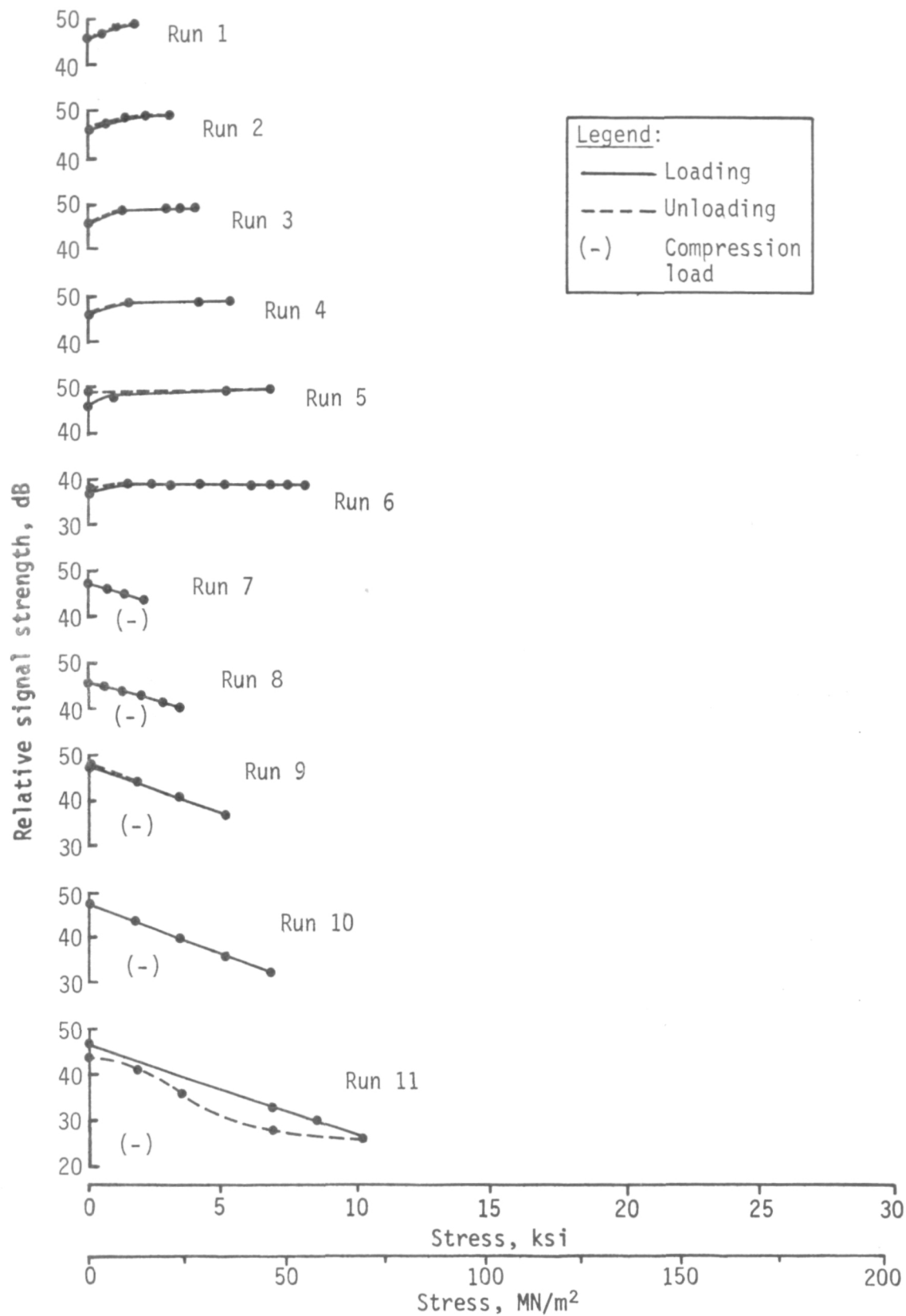


Figure 42. - Signal strength vs stress for cylindrical specimen with 9.5-mm (3/8-in.) defect.

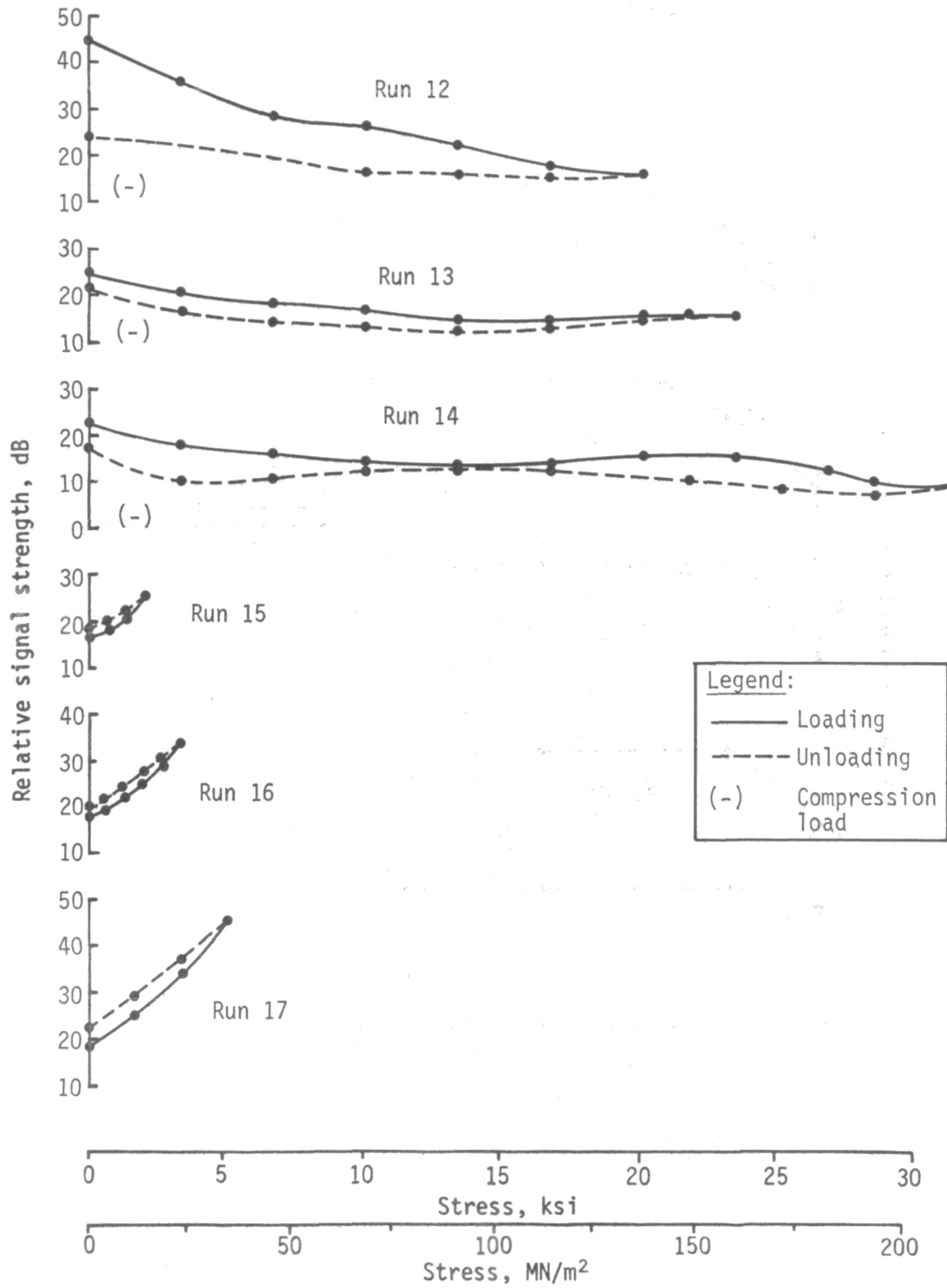


Figure 42. - Continued.

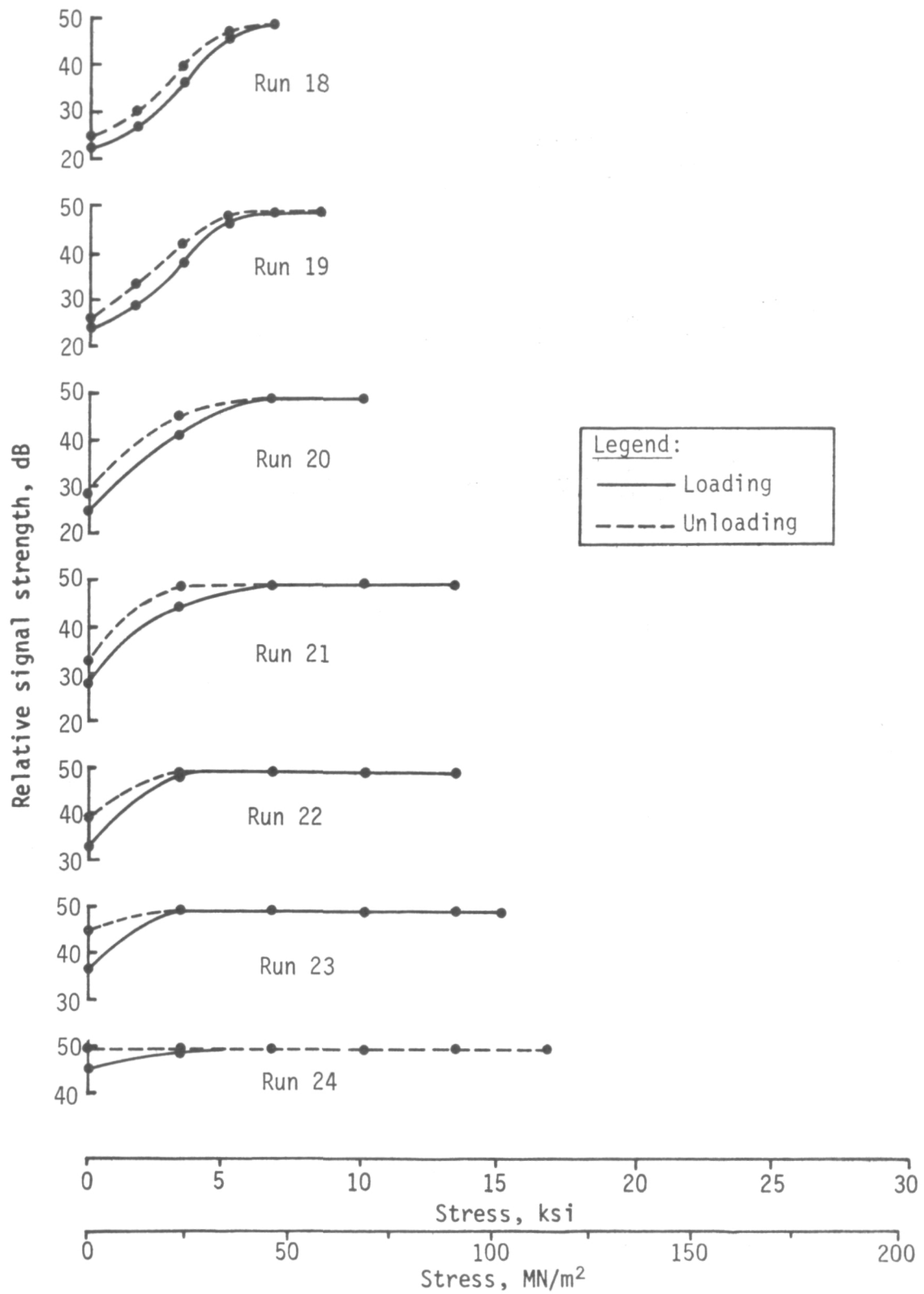


Figure 42. - Concluded.

TABLE IX. - EFFECT OF LOADING ON ULTRASONIC SIGNAL STRENGTH FOR
CYLINDRICAL SPECIMENS WITH 11-mm (7/16-in.) DEFECT

Specimen no.	Run no.	Initial signal strength at zero load, dB	Maximum load,		Maximum stress,		Signal strength at maximum load, dB	Final signal strength at zero load, dB
			kN	(kip)	MN/m ²	(ksi)		
R-6	1	20.0	89	(20)	46.2	(6.7)	38.0	25.5
	2	26.0	111	(25)	57.9	(8.4)	39.5	31.0
	3	31.5	133	(30)	69.6	(10.1)	39.5	36.0
	4	36.0	156	(35)	81.3	(11.8)	39.5	39.5*
R-12	1	42.7	44	(10)	23.4	(3.4)	50.5	43.7
	2	43.3	67	(15)	34.4	(5.0)	50.7	44.3
	3	43.1	89	(20)	46.2	(6.7)	50.7	44.9
	4	44.9	111	(25)	57.9	(8.4)	50.7	46.7
	5	46.7	133	(30)	69.6	(10.1)	50.9	49.5
	6	49.5	156	(35)	81.3	(11.8)	50.9	51.2*
	7	51.2	-44	(-10)	-23.4	(-3.4)	47.3	51.5
	8	51.5	-67	(-15)	-34.4	(-5.0)	43.5	51.5
	9	51.5	-89	(-20)	-46.2	(-6.7)	39.5	51.5
	10	51.5	-111	(-25)	-57.9	(-8.4)	36.5	52.0
	11	51.3	-133	(-30)	-69.6	(-10.1)	33.7	51.4
	12	51.4	-156	(-35)	-81.3	(-11.8)	29.7	49.0
	13	49.0	-178	(-40)	-93.0	(-13.5)	26.7	45.3
	14	45.3	-400	(-90)	-209	(-30.3)	15.8	28.0
	15	28.0	-445	(-100)	-232	(-33.7)	18.0	25.0
	16	25.0	-578	(-130)	-302	(-43.8)	13.0	42.0
R-16	1	41.0	44	(10)	23.4	(3.4)	46.5	41.0
	2	41.0	67	(15)	34.4	(5.0)	46.7	42.0
	3	41.7	89	(20)	46.2	(6.7)	46.9	43.0
	4	43.0	111	(25)	57.9	(8.4)	46.9	44.9
	5	44.9	133	(30)	69.6	(10.1)	47.0	47.0*
	6	47.0	-67	(-15)	-34.4	(-5.0)	37.2	46.2
	7	46.3	-89	(-20)	-46.2	(-6.7)	32.9	45.7
	8	45.3	-111	(-25)	-57.9	(-8.4)	28.5	45.2
	9	45.2	-133	(-30)	-69.6	(-10.1)	24.7	44.0
	10	44.0	-156	(-40)	-81.3	(-11.8)	17.7	34.2
	11	34.2	-222	(-50)	-116	(-16.8)	14.7	20.2
	12	20.2	-267	(-60)	-139	(-20.2)	12.9	17.2
	13	17.2	-311	(-70)	-163	(-23.6)	11.0	13.5
	14	13.5	-356	(-80)	-185	(-26.9)	9.3	11.7
	15	11.7	-400	(-90)	-209	(-30.3)	9.5	10.2
	16	10.2	-445	(-100)	-232	(-33.7)	10.2	11.0
	17	11.4	44	(10)	23.4	(3.4)	28.5	16.0
	18	15.8	67	(15)	34.4	(5.0)	40.5	20.2
	19	20.2	89	(20)	46.2	(6.7)	47.2	22.9
	20	22.7	111	(25)	57.9	(8.4)	47.7	24.2
	21	24.2	133	(30)	69.6	(10.1)	47.8	25.5
	22	25.3	156	(35)	81.3	(11.8)	48.0	27.2
	23	27.0	178	(40)	93.0	(13.5)	48.0	30.3
	24	30.3	200	(45)	105	(15.2)	47.8	35.1
	25	35.5	222	(50)	116	(16.8)	48.2	44.7
	26	44.7	245	(55)	127	(18.5)	48.2	48.7*
	27	48.7	267	(60)	139	(20.2)	48.0	48.7
* Fill residual defect opening.								

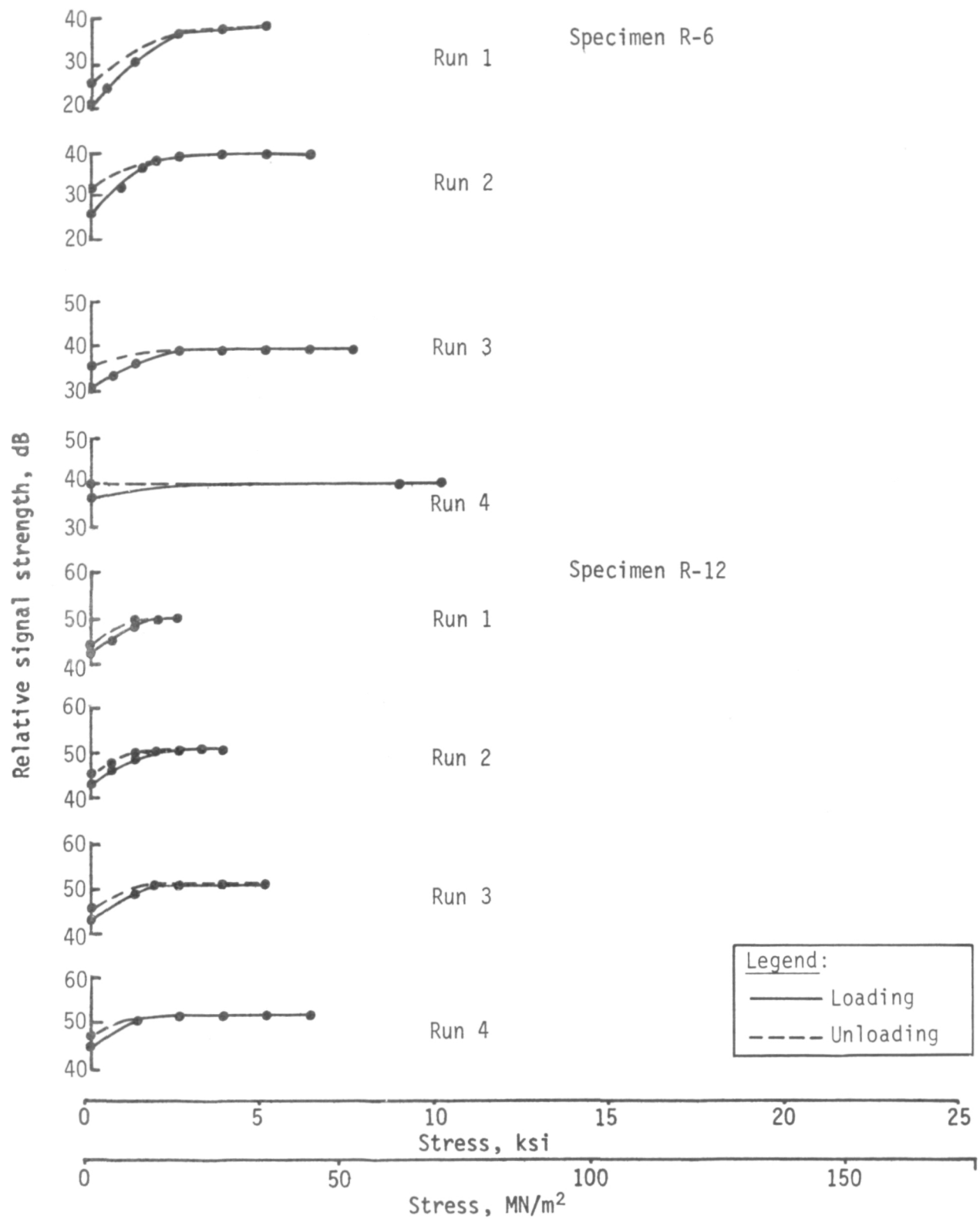


Figure 43. - Signal strength vs stress for cylindrical specimens with 11-mm (7/16-in.) defects.

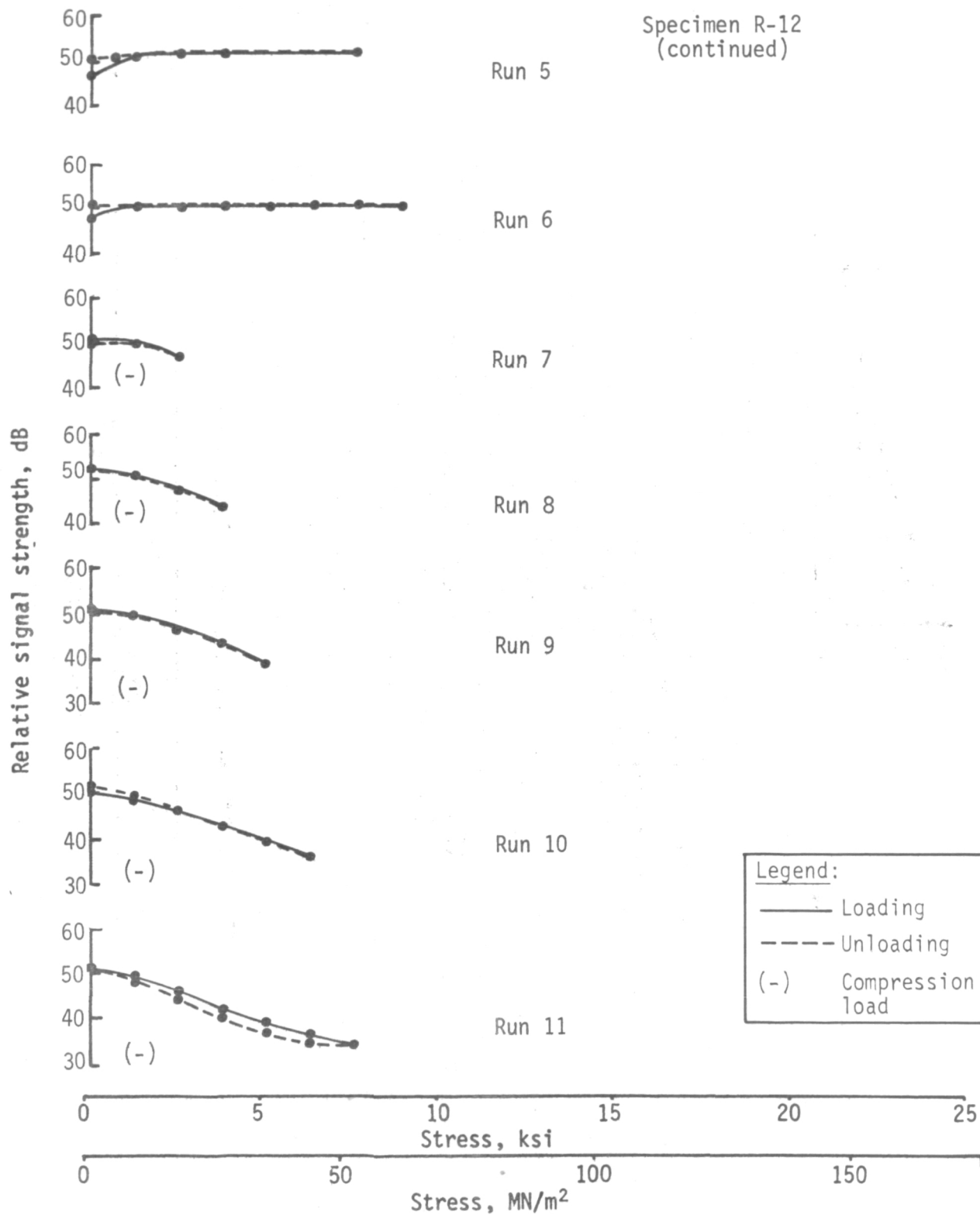
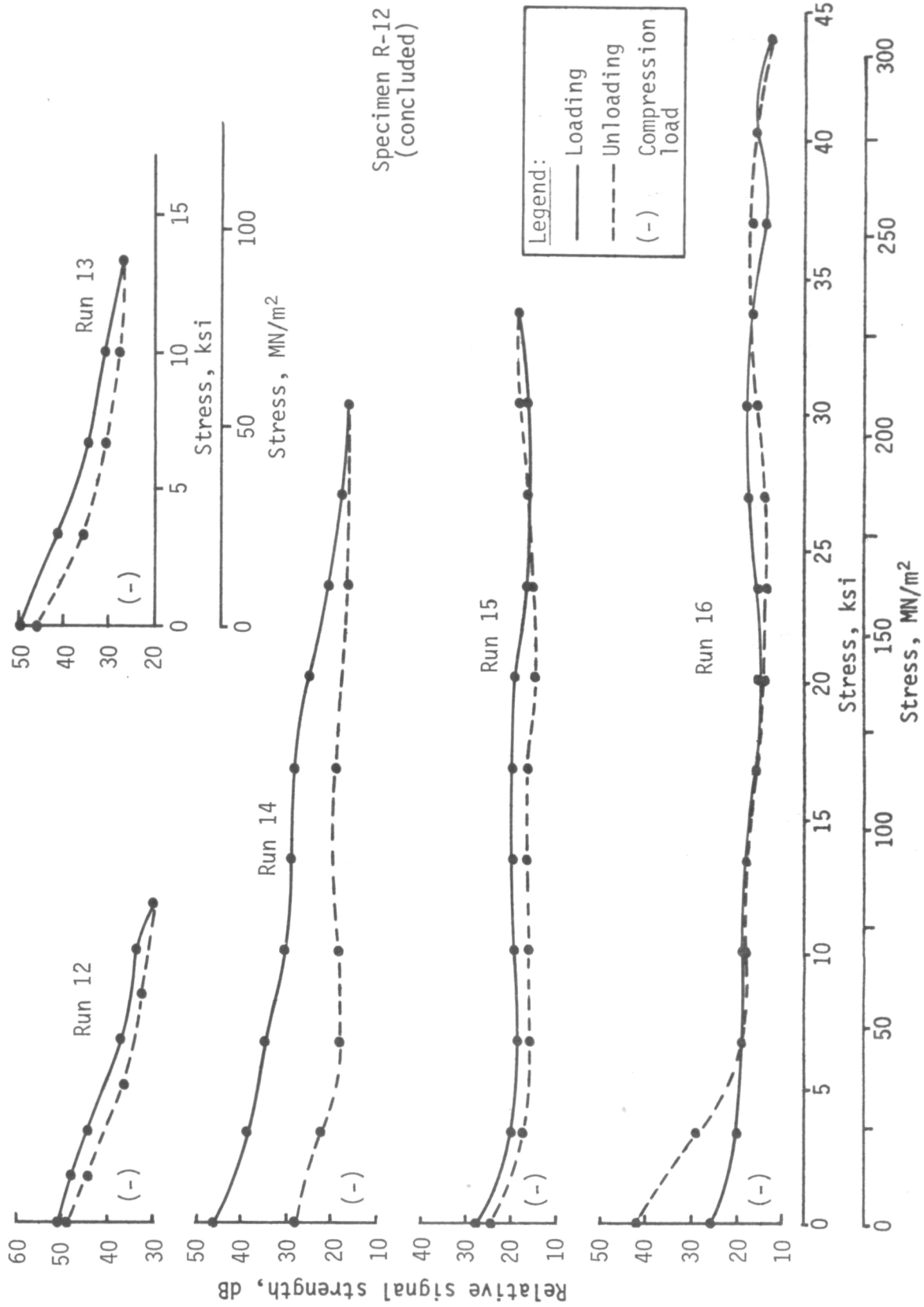


Figure 43. - Continued.



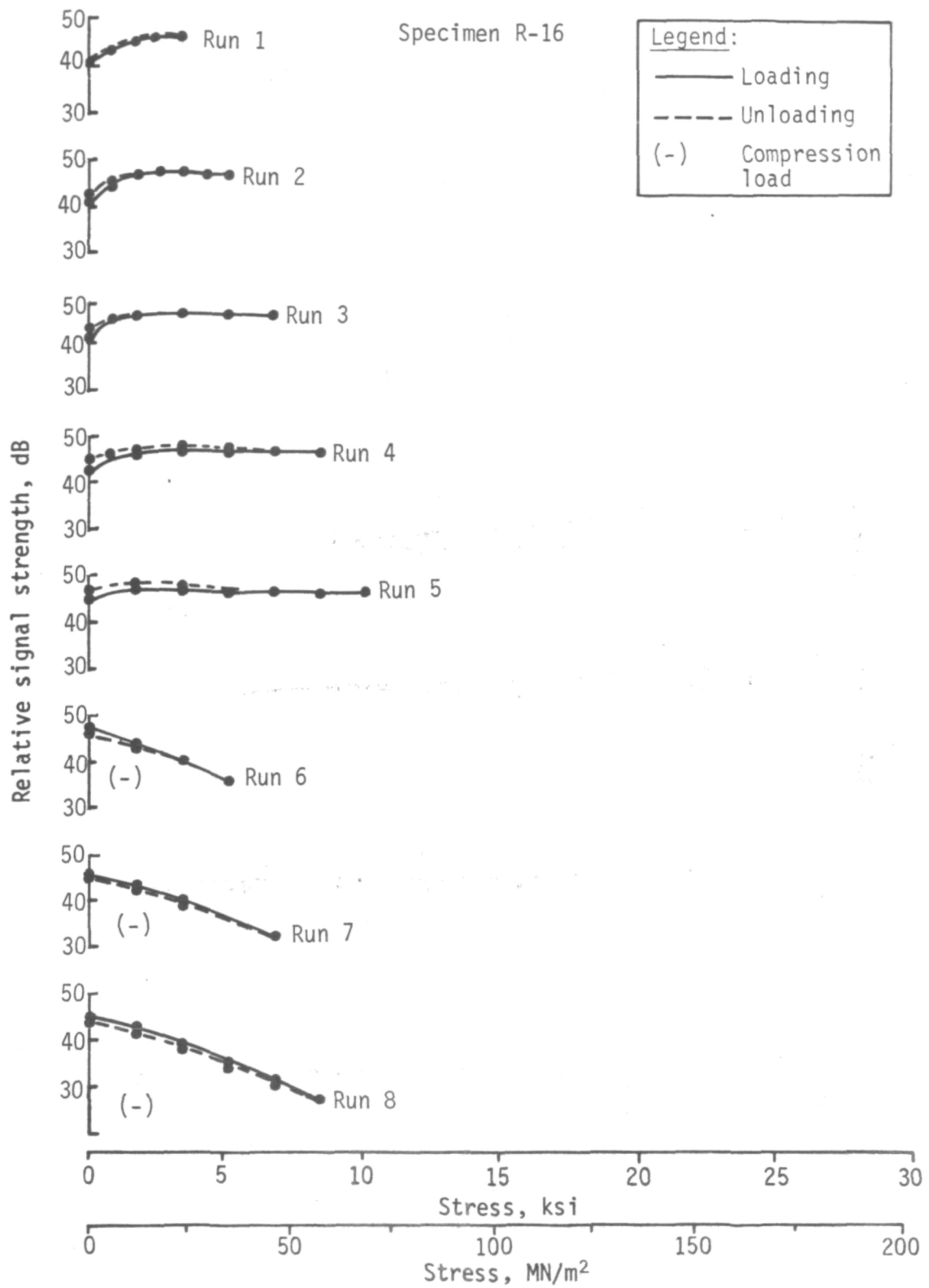


Figure 43. - Continued.

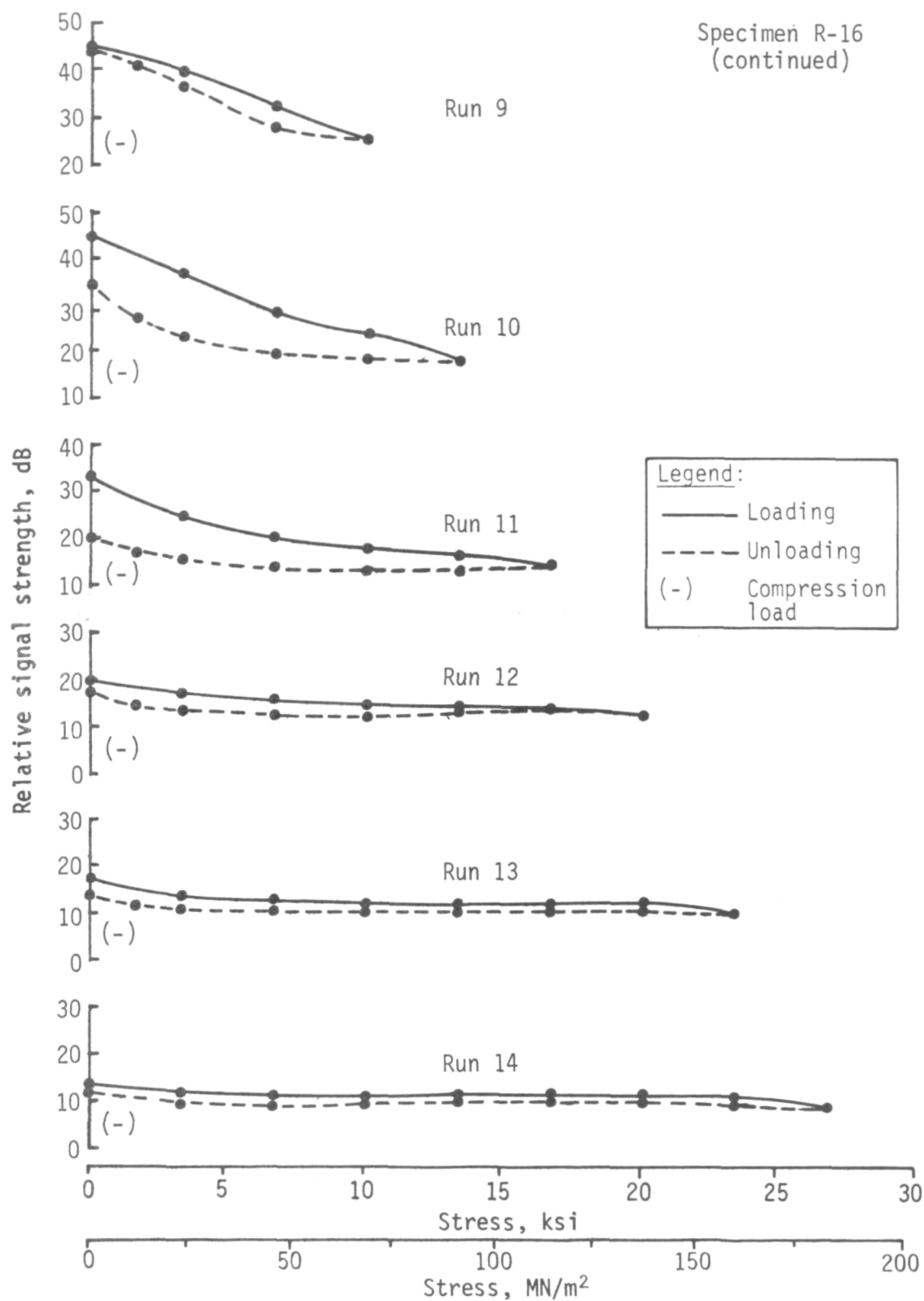


Figure 43. - Continued.

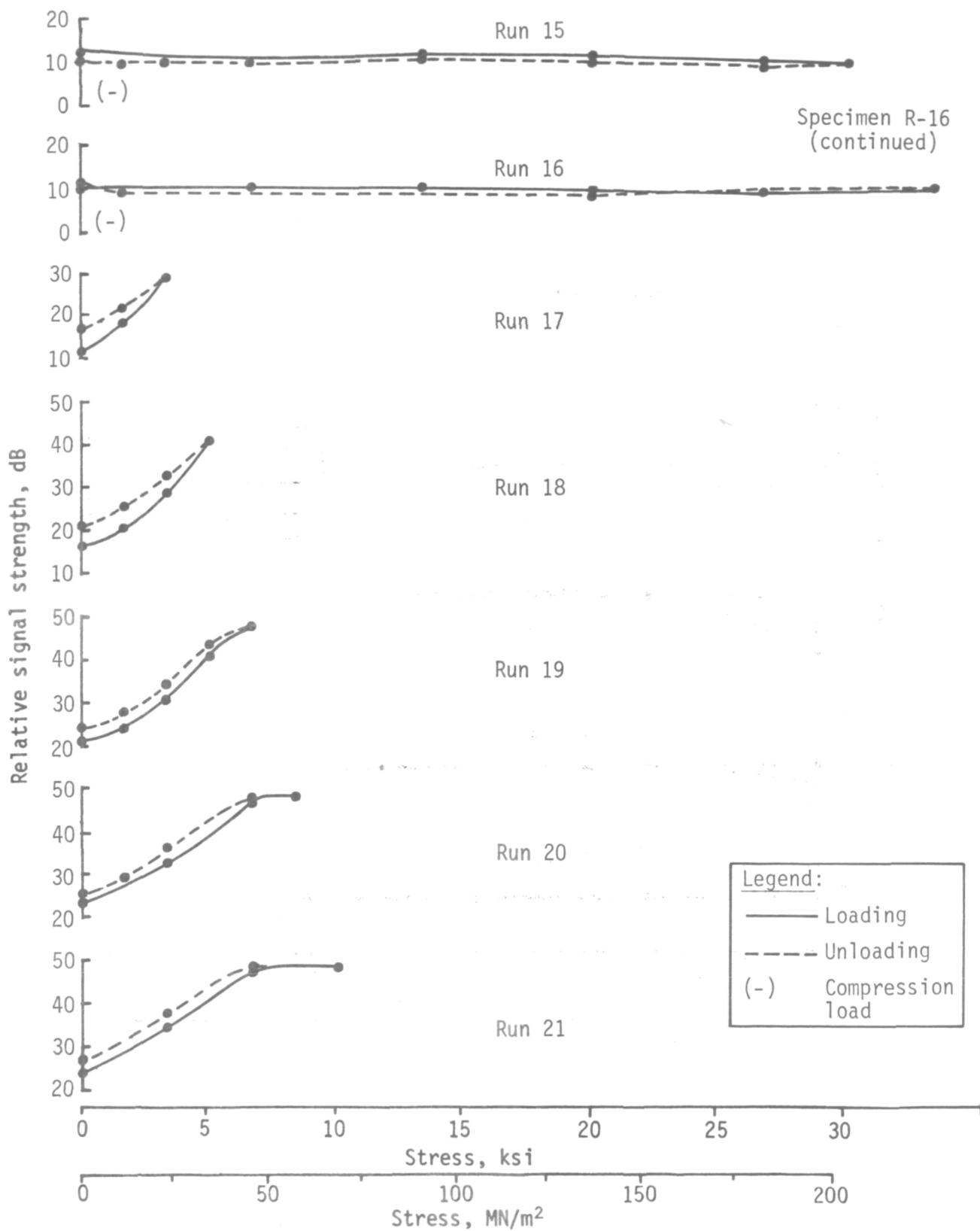


Figure 43. - Continued.

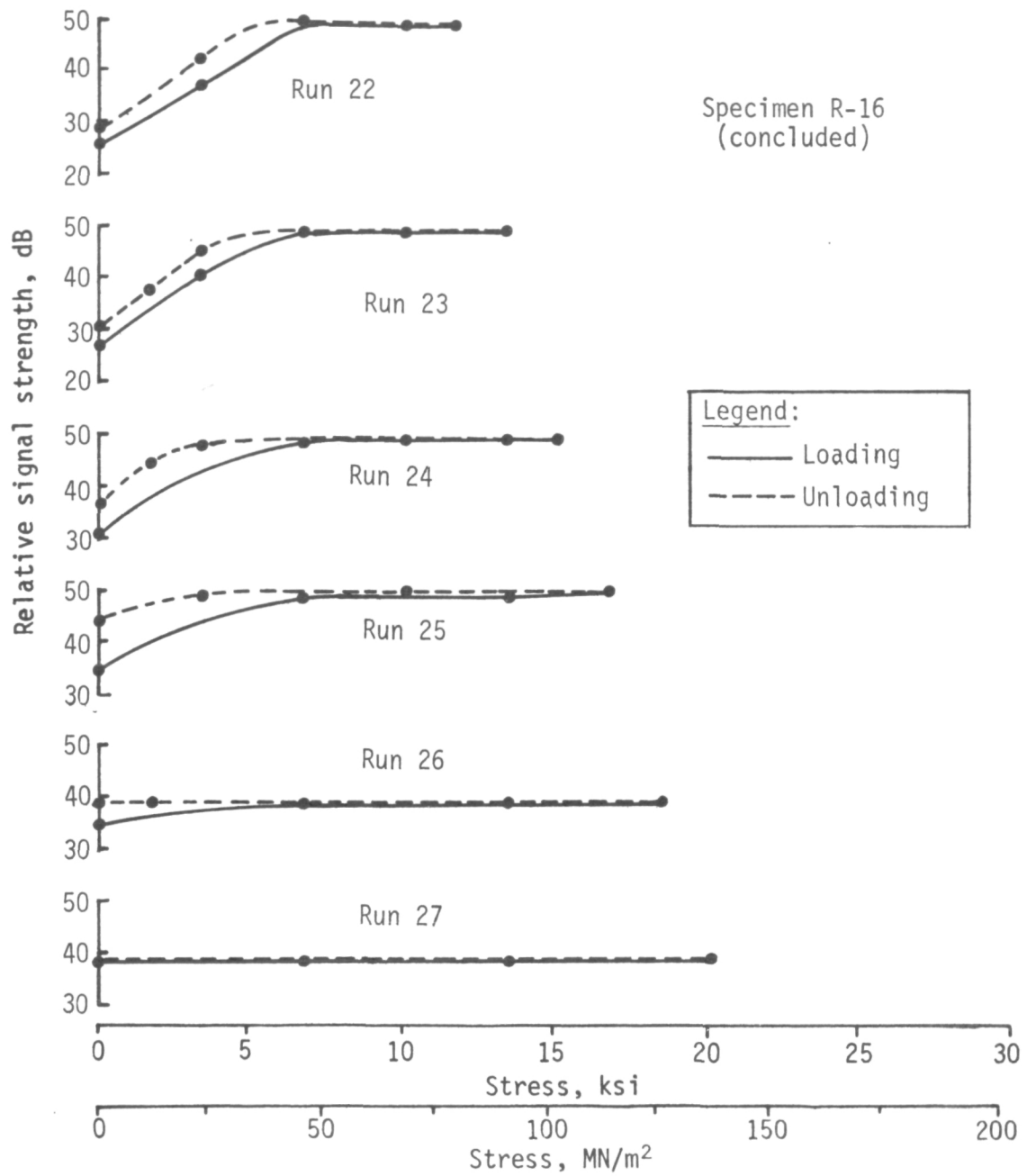


Figure 43. - Concluded.

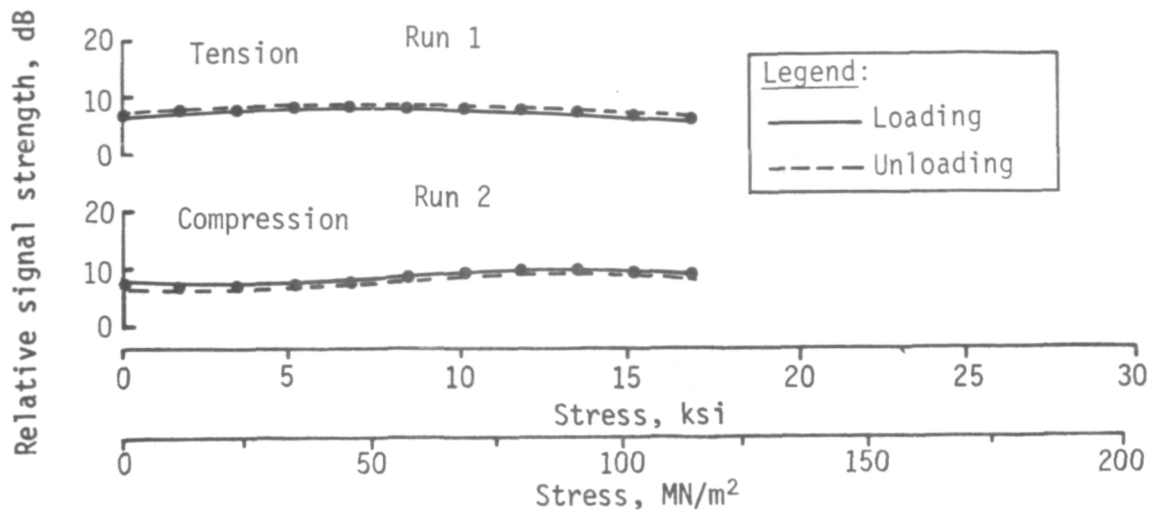
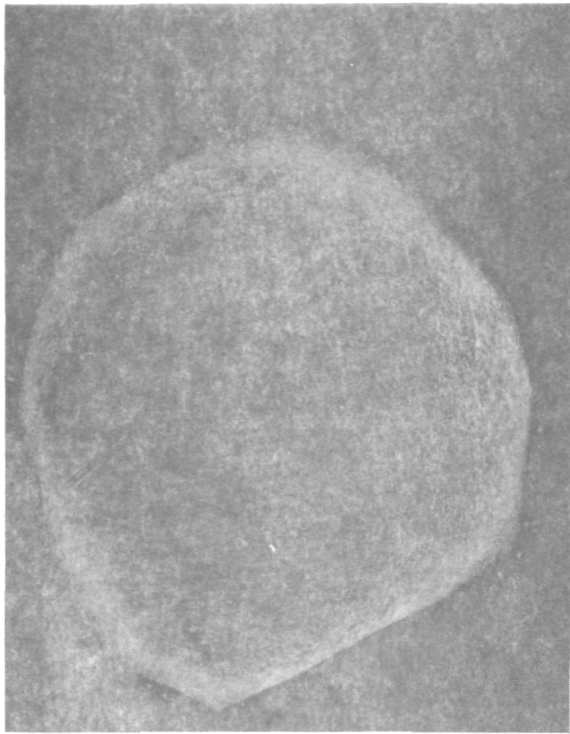


Figure 44. - Signal strength vs stress for fully welded cylindrical specimen.

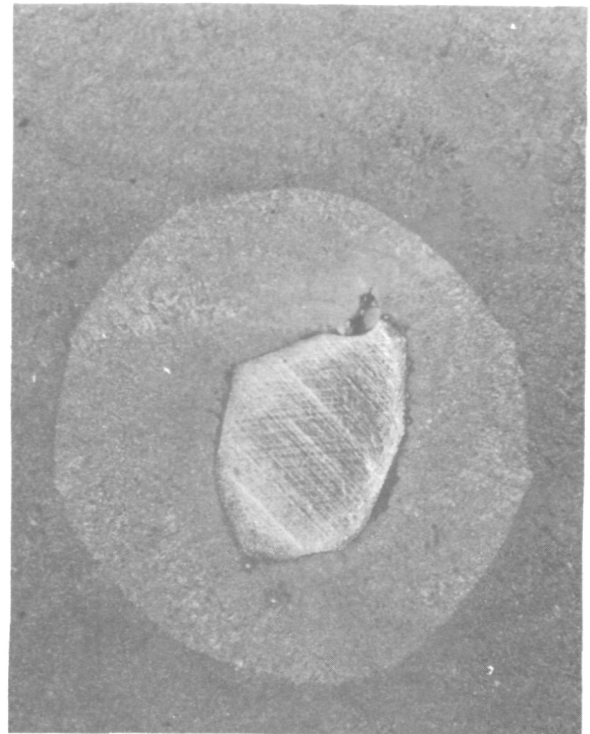
After cyclic testing, specimens were opened to confirm actual defect size and shape. Measurements were made with a planimeter, as previously described. Results are given in Table X, and figure 45 through 47 are photographs of the defects. Note that some defects show cyclic growth bands.

TABLE X. -- SUMMARY OF DEFECT SIZE DATA

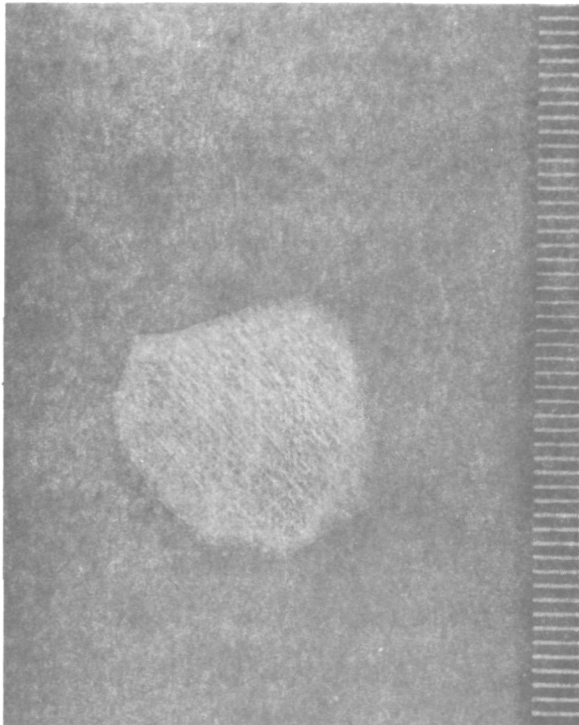
Specimen no.	Desired diameter,		Actual diameter,	
	mm	(in.)	mm	(in.)
R-6	11.1	(0.438)	9.6	(0.376)
R-7	4.8	(0.188)	4.0	(0.158)
R-8	6.4	(0.250)	4.5	(0.178)
R-9	4.8	(0.188)	4.5	(0.178)
R-10	7.9	(0.312)	6.6	(0.260)
R-11	9.5	(0.375)	9.4	(0.372)
R-12	11.1	(0.438)	10.7	(0.420)
R-13	7.9	(0.312)	6.4	(0.252)
R-14	4.8	(0.188)	3.8	(0.148)
R-15	6.4	(0.250)	5.8	(0.230)
R-16	11.1	(0.438)	10.1	(0.396)



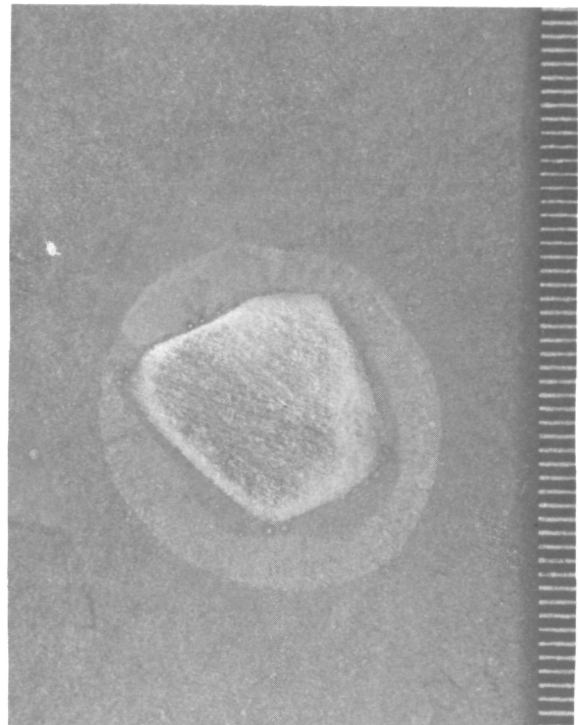
R-6



R-7

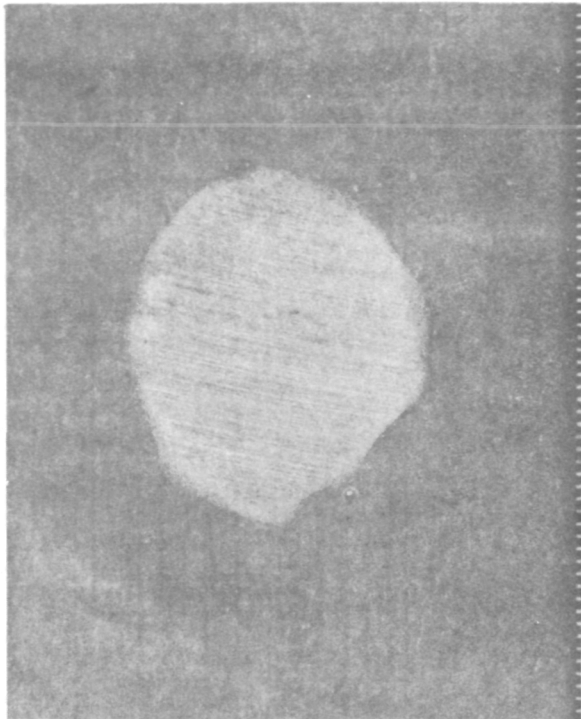


R-8

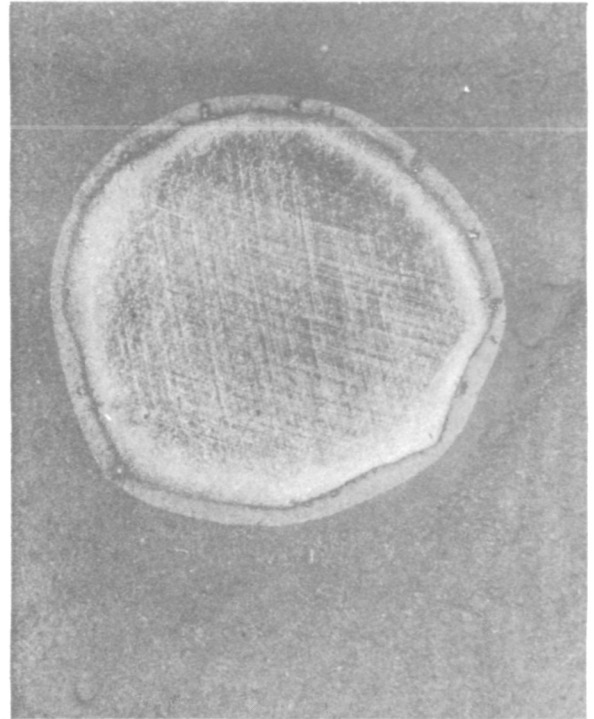


R-9

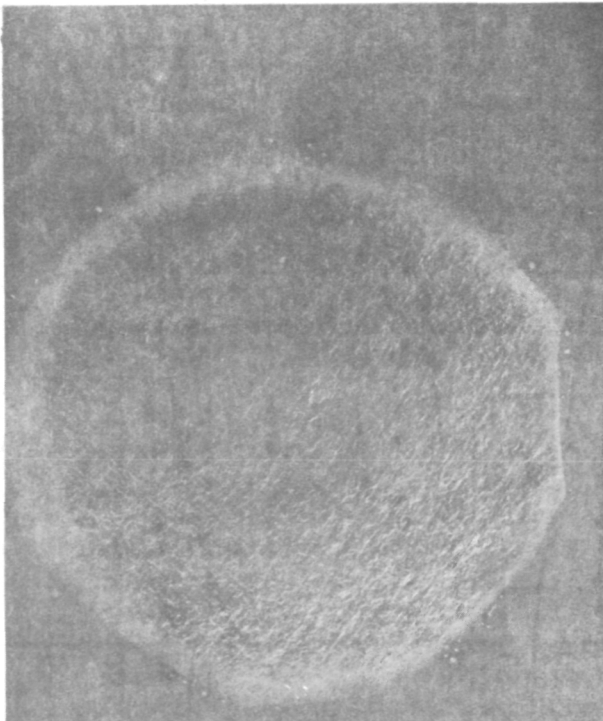
Figure 45. - Lack-of-fusion defects in specimens R-6 through R-9.



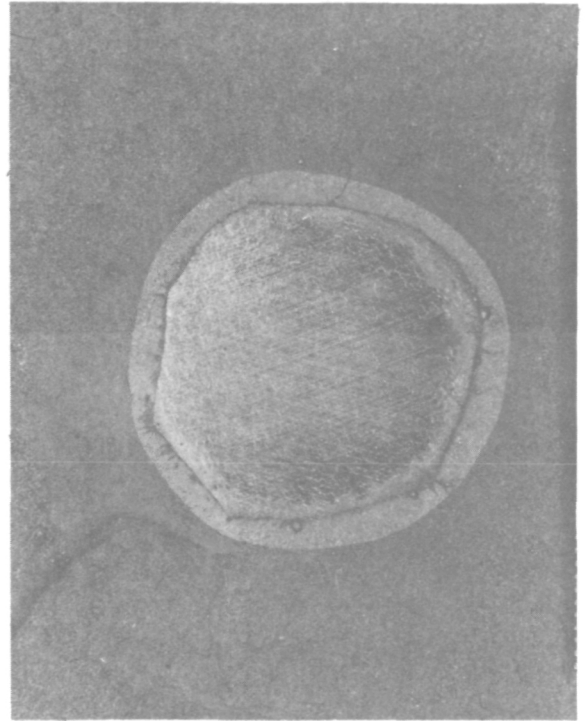
R-10



R-11

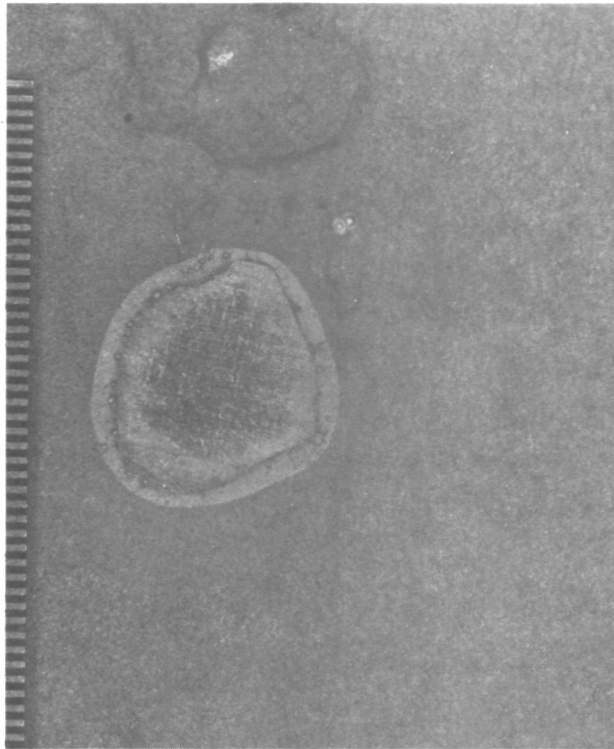


R-12

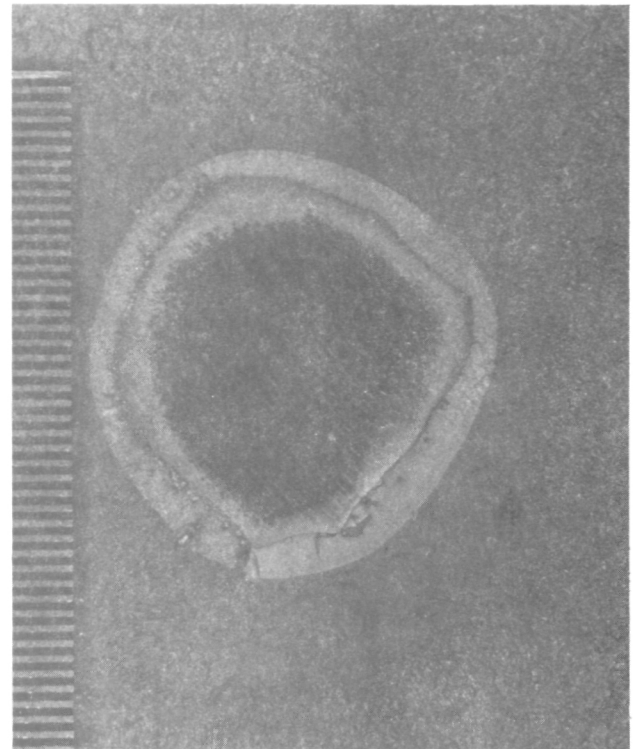


R-13

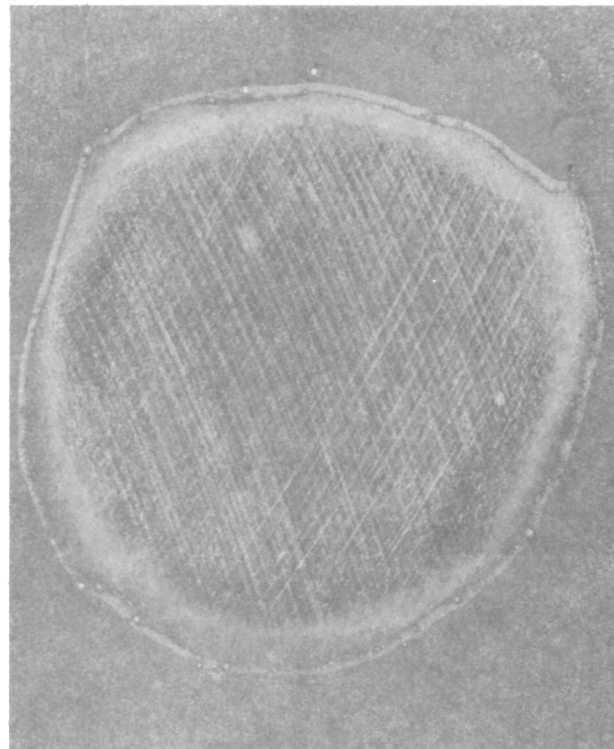
Figure 46. - Lack-of-fusion defects in specimens R-10 through R-13.



R-14



R-15



R-16

Figure 47. - Lack-of-fusion defects in specimens R-14, R-15, and R-16.

Flat Specimens

Two specimens of each nominal defect size were evaluated using the longitudinal-wave pulse-echo technique.

Specimens F-1 and F-2 [4.8-mm (3/16-in.) defect size] were evaluated. Table XI summarizes data for both specimens, and figure 48 is a graphic presentation of the F-1 data. F-1 exhibited full opening at 89 MN/m² (13 ksi). Test specimen F-2 exhibited a slightly higher initial ultrasonic reading and relatively little change during loading and unloading sequences up to 178 MN/m² (26 ksi). It is not clear whether the defect was fully opened after loading to the first level [18 MN/m² (3 ksi)].

Test specimens F-12 and F-15 contained nominal 6.4-mm (1/4 in.) defects. Table XII and figure 49 give the data for this series. F-12 exhibited a tight defect as indicated by an initial ultrasonic strength level approximately the same as the background noise (~12 dB). A stress of 178 MN/m² (26 ksi) was required to achieve full opening. F-15 showed a higher initial signal strength (18.7 dB) and became fully opened at 125 MN/m² (18 ksi).

The 7.9-mm (5/16-in.) defect specimens were identified as F-20 and F-23, data for which are shown in Table XIII and figure 50. F-20 exhibited a tight flaw (14-dB initial reading) and required 178 MN/m² (26 ksi) for full opening. F-23 showed a higher initial ultrasonic signal strength (~25 dB). The loading data indicate that the defect may have been fully opened during the first loading cycle at 18 MN/m² (3 ksi).

The 9.5-mm (3/8-in.) defect specimens (F-30 and F-35) showed similar behavior. Table XIV summarizes data for both specimens. Figure 51 graphically shows data for specimen F-35. Both flaws were tight (initial signal strengths were 13.0 and 14.8, respectively). Specimen F-30 was loaded to 142 MN/m² (21 ksi) and showed evidence of approaching full opening. F-35 was loaded to 178 MN/m² (26 ksi) and exhibited full residual flaw opening.

Two specimens of the largest nominal-size defect [11.1 mm (7/16 in.)] were evaluated. Table XV gives the data for specimens F-42 and F-44. Figure 52 shows graphic data for F-44.

Specimen F-44 exhibited an initial signal strength of 16.7 dB and showed full opening at 160 MN/m² (23 ksi). F-44 exhibited

TABLE XI. - EFFECT OF LOADING ON ULTRASONIC SIGNAL STRENGTH FOR
FLAT SPECIMENS WITH 4.8-mm (3/16-in.) DEFECT

Specimen no.	Run no.	Initial signal strength at zero load, dB	Maximum load,		Maximum stress,		Signal strength at maximum load, dB	Final signal strength at zero load, dB
			kN	(kip)	MN/m ²	(ksi)		
F-1	1	20.0	44	(10)	18	(2.6)	20.7	20.0
	2	20.0	89	(20)	36	(5.2)	25.0	20.0
	3	20.0	133	(30)	53	(7.7)	29.2	17.0
	4	17.0	178	(40)	71	(10.3)	31.7	21.0
	5	21.0	222	(50)	89	(12.9)	31.7	31.0*
F-2	1	24.2	44	(10)	18	(2.6)	29.3	24.3
	2	24.3	89	(20)	36	(5.2)	29.1	25.3
	3	25.3	133	(30)	53	(7.7)	29.7	26.3
	4	26.3	178	(40)	71	(10.3)	30.9	28.2
	5	28.2	222	(50)	89	(12.9)	31.8	25.3
	6	25.3	267	(60)	107	(15.5)	31.8	28.3
	7	28.3	311	(70)	125	(18.1)	32.1	28.5
	8	28.5	356	(80)	142	(20.6)	32.3	28.8
	9	28.8	400	(90)	160	(23.2)	32.5	29.1
	10	29.1	445	(100)	178	(25.8)	32.8	29.7

* Full residual crack opening.

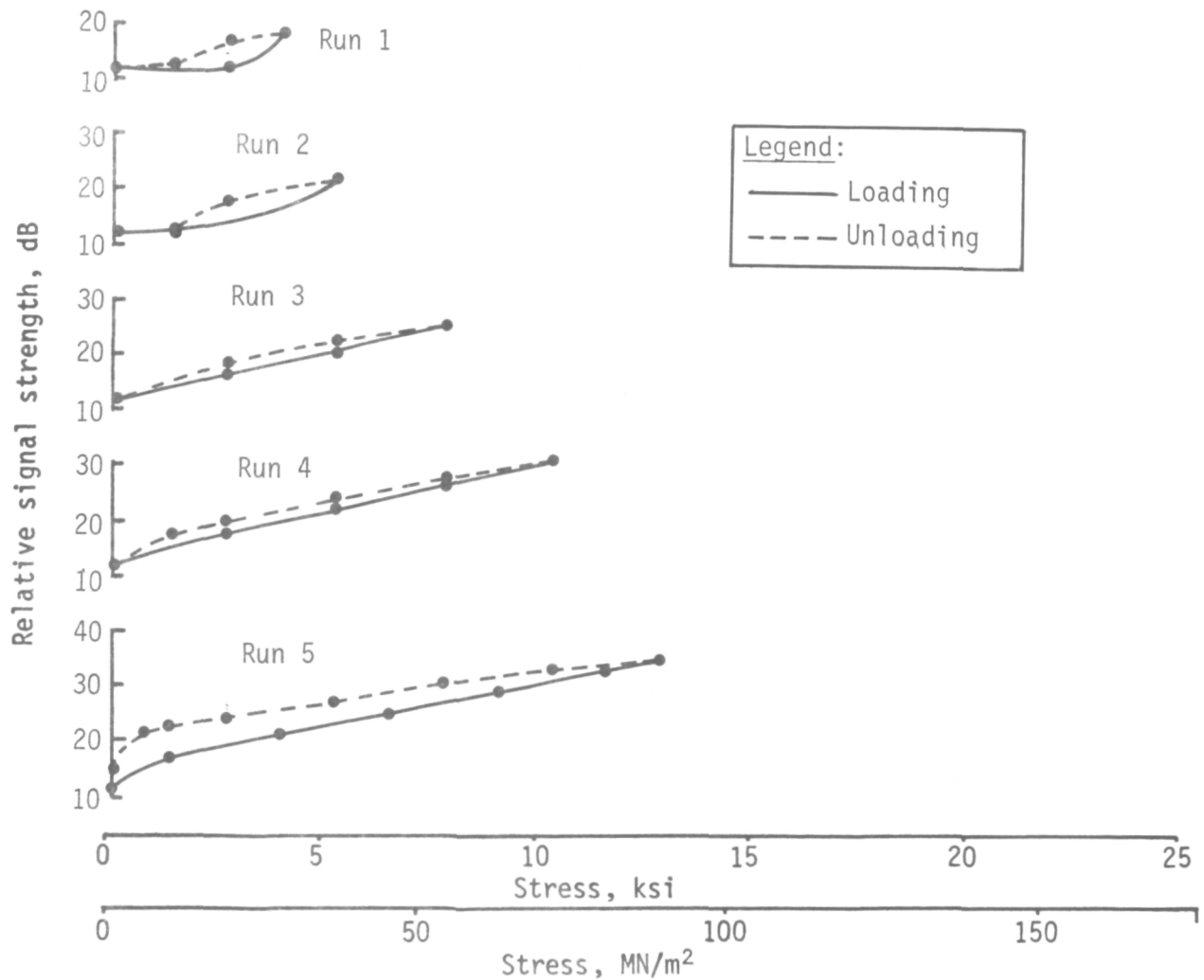


Figure 48. - Signal strength vs stress for specimen F-12.

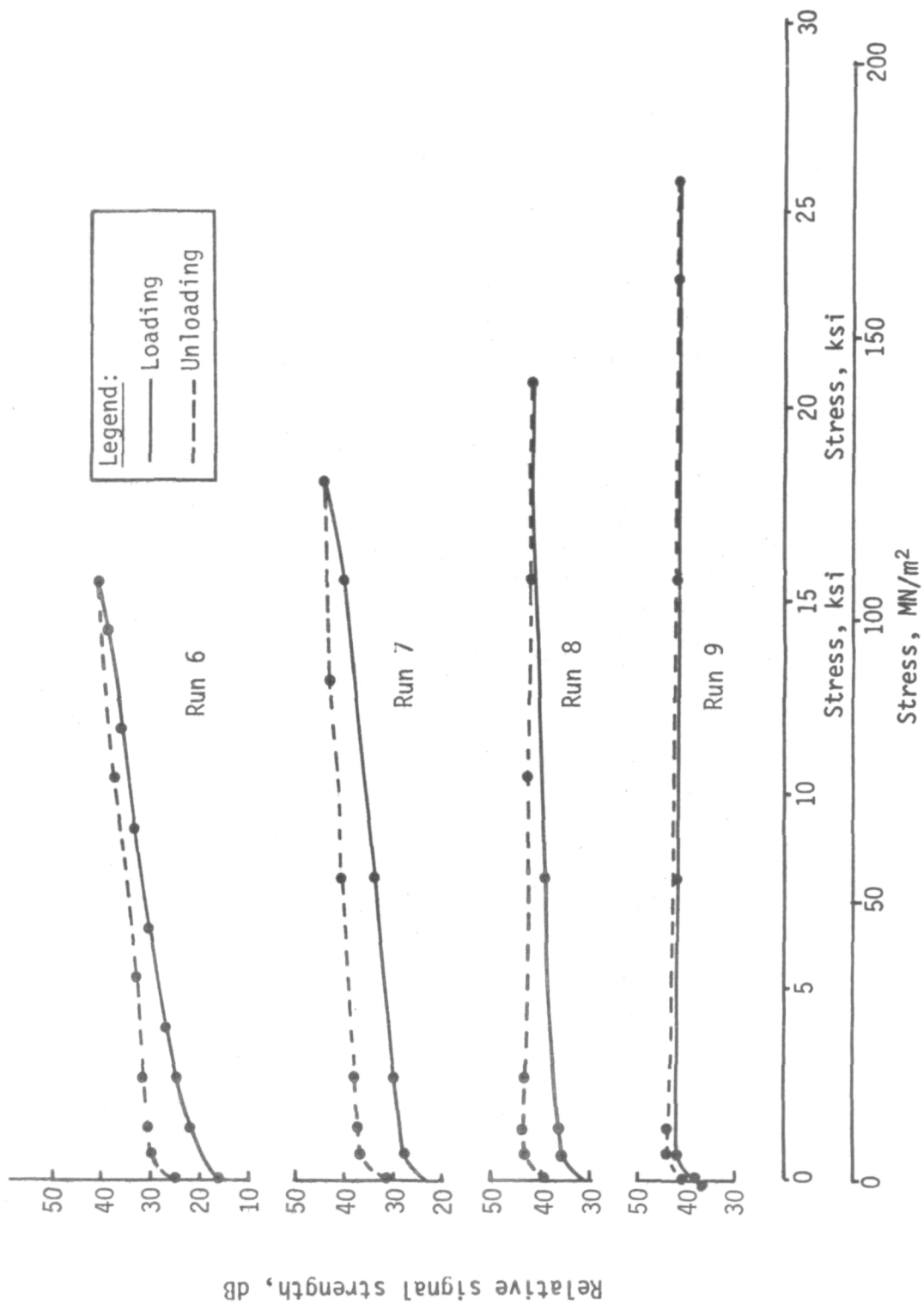


Figure 48. - Concluded.

TABLE XII. - EFFECT OF LOADING ON ULTRASONIC SIGNAL STRENGTH
FOR FLAT SPECIMENS WITH 6.4-mm (1/4-in.) DEFECT

Specimen no.	Run no.	Initial signal strength at zero load, dB	Maximum load,		Maximum stress,		Signal strength at maximum load, dB	Final signal strength at zero load, dB
			kN	(kip)	MN/m ²	(ksi)		
F-12	1	~12	67	(15)	27	(3.9)	19.4	~12
	2	~12	89	(20)	38	(5.2)	22.0	~12
	3	~12	133	(30)	53	(7.7)	25.7	~12
	4	~12	178	(40)	71	(10.3)	31.4	~12
	5	~12	222	(50)	89	(12.9)	35.4	14.3
	6	14.3	267	(60)	107	(15.5)	39.0	22.7
	7	22.7	311	(70)	125	(18.1)	43.0	29.7
	8	29.7	356	(80)	142	(20.6)	41.7	38.0
	9	38.0	445	(100)	178	(25.8)	41.8	40.3*
F-15	1	18.7	44	(10)	18	(2.6)	22.8	19.8
	2	19.4	89	(20)	36	(5.2)	27.1	20.7
	3	20.7	133	(30)	53	(7.7)	29.9	21.9
	4	21.9	178	(40)	71	(10.3)	29.8	24.1
	5	24.1	222	(50)	89	(12.9)	32.9	27.2
	6	27.2	267	(50)	107	(15.5)	34.7	30.9
	7	30.9	311	(70)	125	(18.1)	34.5	34.9*

* Fill residual crack opening.

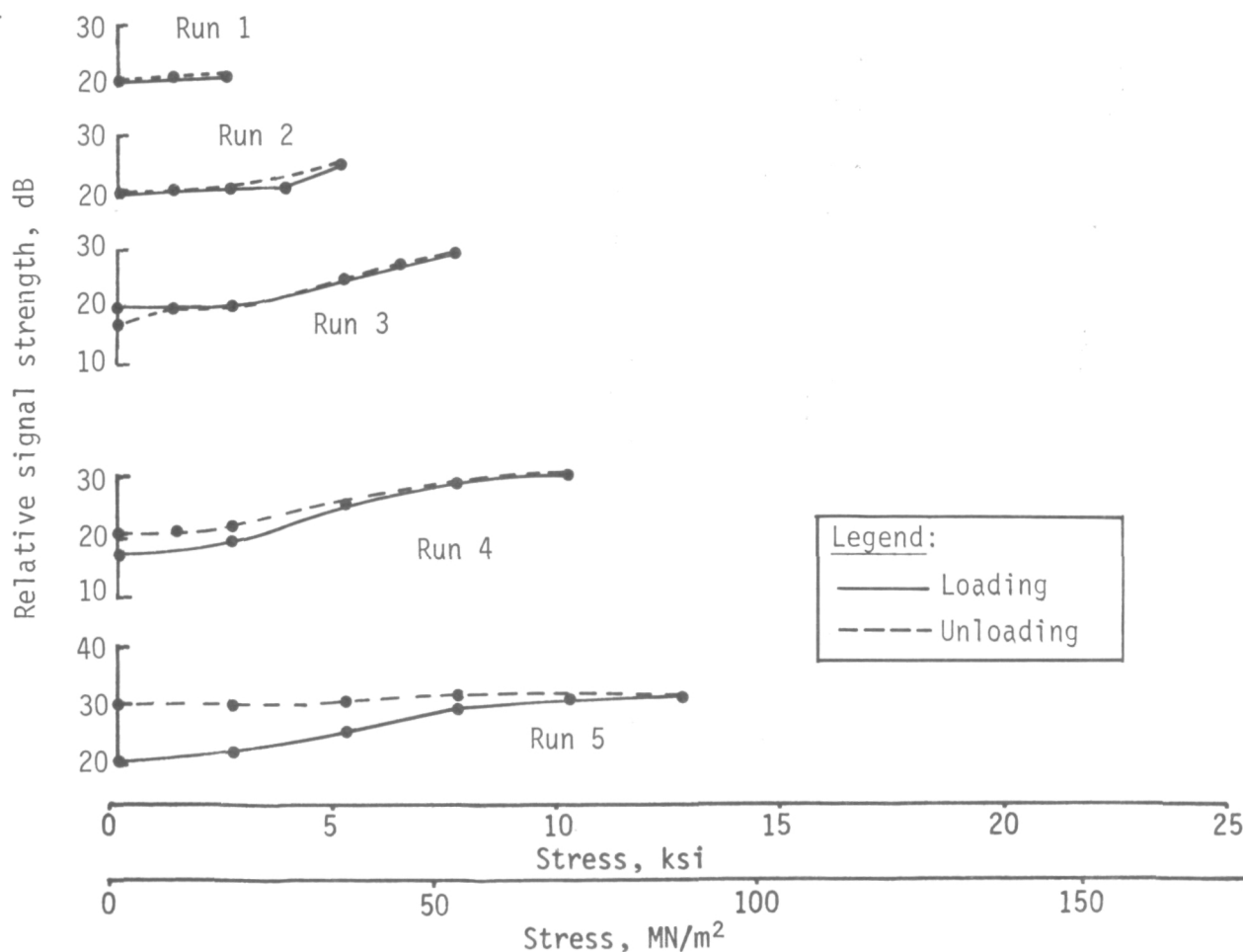


Figure 49. - Signal strength vs stress for specimen F-1.

TABLE XIII. - EFFECT OF LOADING ON ULTRASONIC SIGNAL STRENGTH
FOR FLAT SPECIMENS WITH 7.9-mm (5/16-in.) DEFECT

Specimen no.	Run no.	Initial signal strength at zero load, dB	Maximum load,		Maximum stress,		Signal strength at maximum load, dB	Final signal strength at zero load, dB
			kN	(kip)	MN/m ²	(ksi)		
F-20	1	14.0	44	(10)	18	(2.6)	14.0	14.0
	2	14.0	89	(20)	36	(5.2)	14.5	14.0
	3	14.0	133	(30)	53	(7.7)	17.5	14.3
	4	14.3	178	(40)	71	(10.3)	22.0	14.8
	5	14.8	222	(50)	89	(12.9)	25.8	15.0
	6	15.0	267	(60)	107	(15.5)	28.5	15.1
	7	15.1	311	(70)	125	(18.1)	30.5	16.0
	8	16.0	356	(80)	142	(20.6)	32.3	21.0
	9	21.0	400	(90)	160	(23.2)	32.5	29.0
	10	29.0	445	(100)	178	(25.8)	32.7	31.5*
F-23	1	25.3	44	(10)	18	(2.6)	24.9	25.3
	2	25.3	89	(20)	36	(5.2)	25.6	24.5
	3	24.5	133	(30)	53	(7.7)	24.3	25.2
	4	25.2	178	(40)	71	(10.3)	25.8	26.1
	5	26.1	222	(50)	89	(12.9)	27.0	29.3
	6	29.3	267	(60)	107	(15.5)	30.2	39.3
	7	39.3	311	(70)	125	(18.1)	36.9	32.9
	8	32.9	356	(80)	142	(20.6)	46.2	37.1
	9	37.1	400	(90)	160	(23.2)	46.3	40.2
	10	40.2	445	(100)	178	(25.8)	46.6	40.2
	11	40.2	489	(110)	196	(28.4)	47.0	40.2
	12	40.2	534	(120)	214	(31.0)	46.9	39.7

* Full residual crack opening.

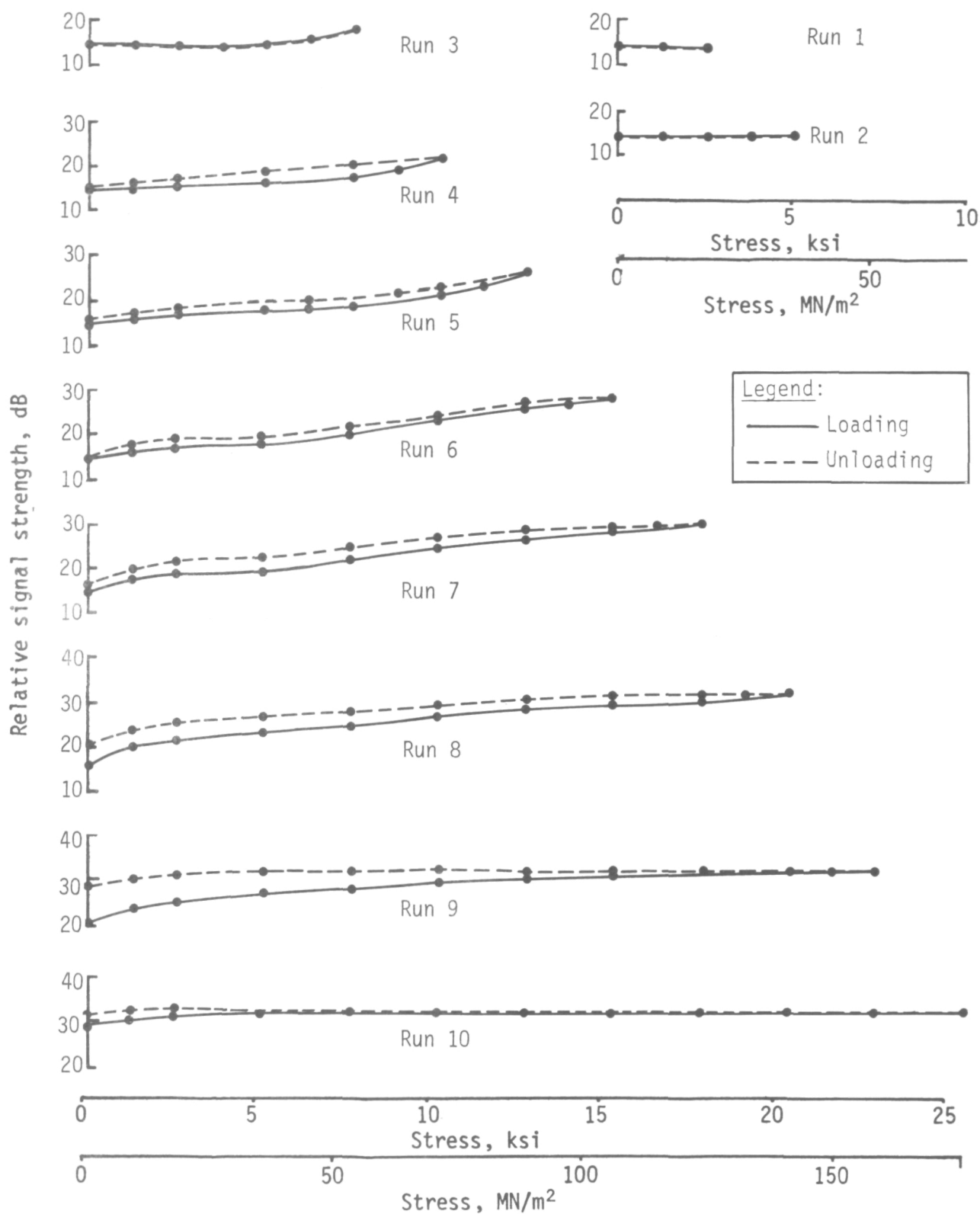


Figure 50. - Signal strength vs stress for specimen F-20.

TABLE XIV. - EFFECT OF LOADING ON ULTRASONIC SIGNAL STRENGTH
FOR FLAT SPECIMENS WITH 9.5-mm (3/8-in.) DEFECT

Specimen no.	Run no.	Initial signal strength at zero load, dB	Maximum load,		Maximum stress,		Signal strength at maximum load, dB	Final signal strength at zero load, dB
			kN	(kip)	MN/m ²	(ksi)		
F-30	1	13.0	22	(5)	9	(1.3)	13.0	13.0
	2	13.0	89	(20)	36	(5.2)	14.3	11.7
	3	11.7	133	(30)	53	(7.7)	14.9	12.7
	4	12.7	178	(40)	71	(10.3)	14.7	12.2
	5	12.2	222	(50)	89	(12.9)	21.5	12.2
	6	~12	267	(60)	107	(15.5)	24.9	~12
	7	~12	311	(70)	125	(18.1)	28.2	14.9
	8	14.9	356	(80)	142	(20.6)	37.8	24.7
F-35	1	14.8	44	(10)	18	(2.6)	14.2	14.2
	2	14.2	89	(20)	36	(5.2)	15.2	14.7
	3	14.7	133	(30)	53	(7.7)	13.8	14.9
	4	14.9	178	(40)	71	(10.3)	14.7	14.0
	5	14.0	222	(50)	89	(12.9)	18.9	14.7
	6	14.7	267	(60)	107	(15.5)	26.3	16.7
	7	16.7	311	(70)	125	(18.1)	32.9	18.5
	8	18.5	356	(80)	142	(20.6)	38.0	24.2
	9	24.2	400	(90)	160	(23.2)	38.0	35.3
	10	35.3	445	(100)	178	(25.8)	38.2	39.5*
* Fill residual crack opening.								

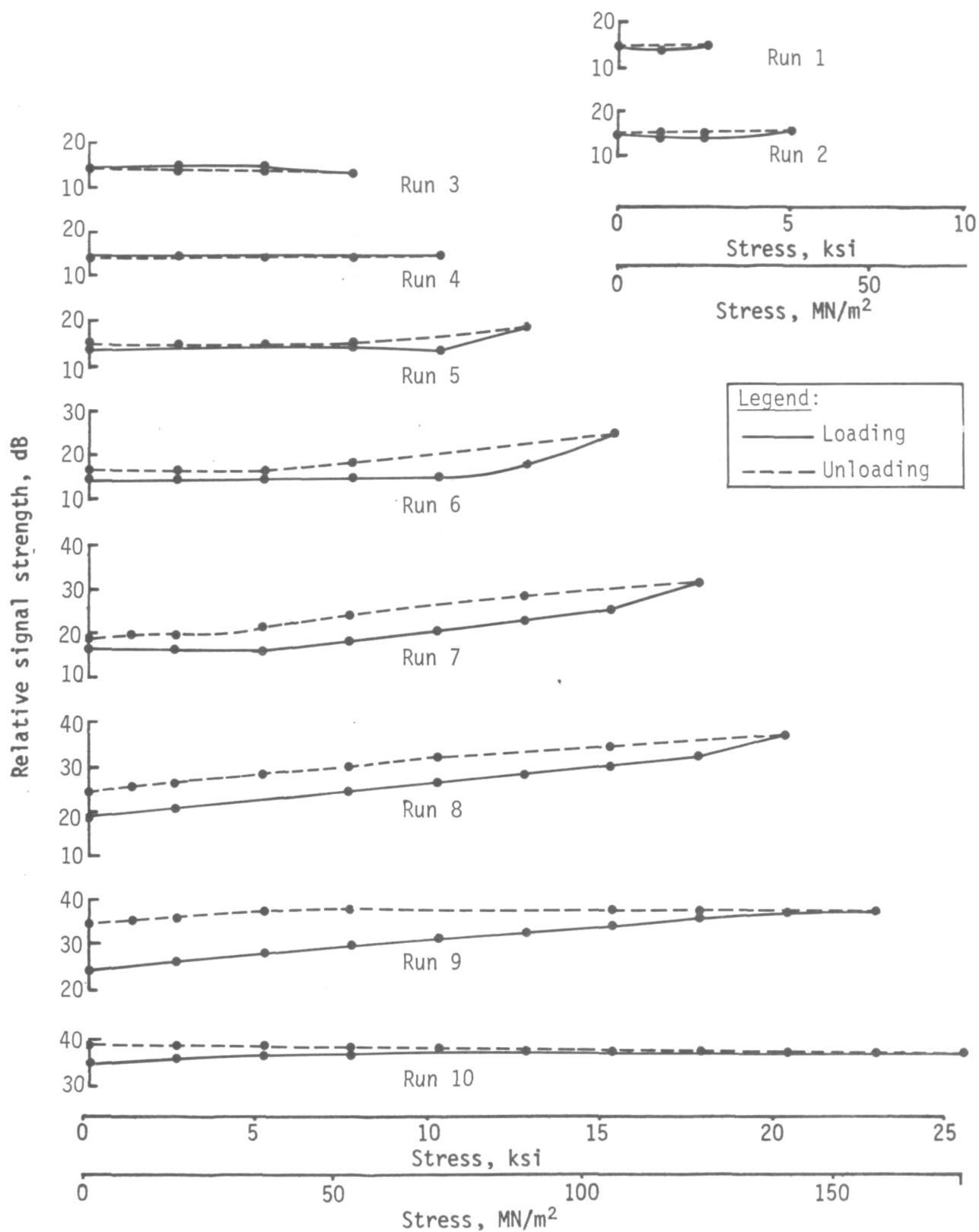


Figure 51. - Signal strength vs stress for specimen F-35.

TABLE XV. - EFFECT OF LOADING ON ULTRASONIC SIGNAL STRENGTH FOR
FLAT SPECIMENS WITH 11.1-mm (7/16-in.) DEFECT

Specimen no. & location	Run no.	Initial signal strength at zero load, dB	Maximum load,		Maximum stress,		Signal strength at maximum load, dB	Final signal strength at zero load, dB
			kN	(kip)	MN/m ²	(ksi)		
F-42 on center- line	1	16.7	44	(10)	18	(2.6)	16.9	16.7
	2	16.7	89	(20)	36	(5.2)	15.8	16.7
	3	16.7	133	(30)	53	(7.7)	18.0	15.0
	4	15.0	178	(40)	71	(10.3)	18.0	16.0
	5	16.0	222	(50)	89	(12.9)	27.3	13.3
	6	13.3	267	(60)	107	(15.5)	36.9	15.5
	7	15.5	311	(70)	125	(18.1)	41.3	22.0
	8	22.0	356	(80)	142	(20.6)	44.9	35.3
	9	35.3	400	(90)	160	(23.2)	43.4	45.2*
F-44 D	1	32.2	22	(5)	9	(1.3)	32.5	32.7
A	2	~8	22	(5)	9	(1.3)	~8	~8
B	3	16.6	22	(5)	9	(1.3)	16.6	16.6
C	4	33.3	89	(20)	36	(5.2)	35.2	32.1
B	5	18.0	89	(20)	36	(5.2)	20.0	17.5
A	6	~8	89	(20)	36	(5.2)	~8	~8
D	7	30.0	89	(20)	36	(5.2)	32.0	30.0
C	8	33.3	178	(40)	71	(10.3)	34.7	32.0
B	9	18.0	178	(40)	71	(10.3)	23.5	16.0
A	10	~8	178	(40)	71	(10.3)	~8	~8
D	11	32.2	178	(40)	71	(10.3)	32.5	31.8
E	12	19.7	156	(35)	62	(9.0)	19.0	19.3
B	13	17.0	400	(90)	160	(23.2)	42.3	36.4
C	14	41.3	400	(90)	160	(23.2)	43.8	42.9
A	15	31.0	-445	(-100)	-178	(-25.8)	~8	14.0
C	16	37.8	-712	(-160)	-285	(-41.3)	~8	31.5

A = Transducer axis on centerline; B = 5 mm (0.2 in.) from centerline; C = 11.4 mm (0.45 in.) from centerline; D = 17.8 mm (0.70 in.) from centerline; E = 24.1 mm (0.95 in.) from centerline.

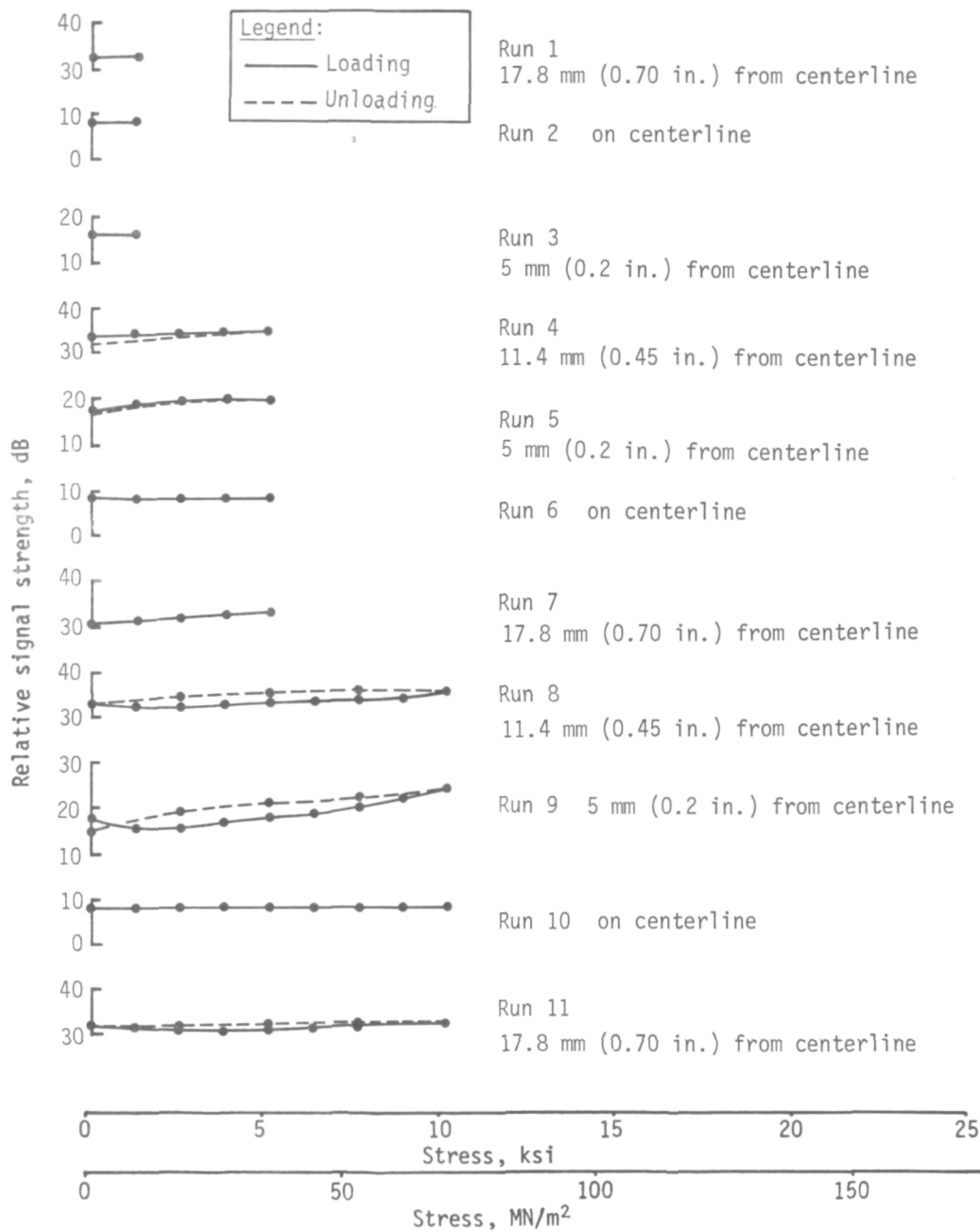


Figure 52. - Signal strength vs stress for specimen F-44.

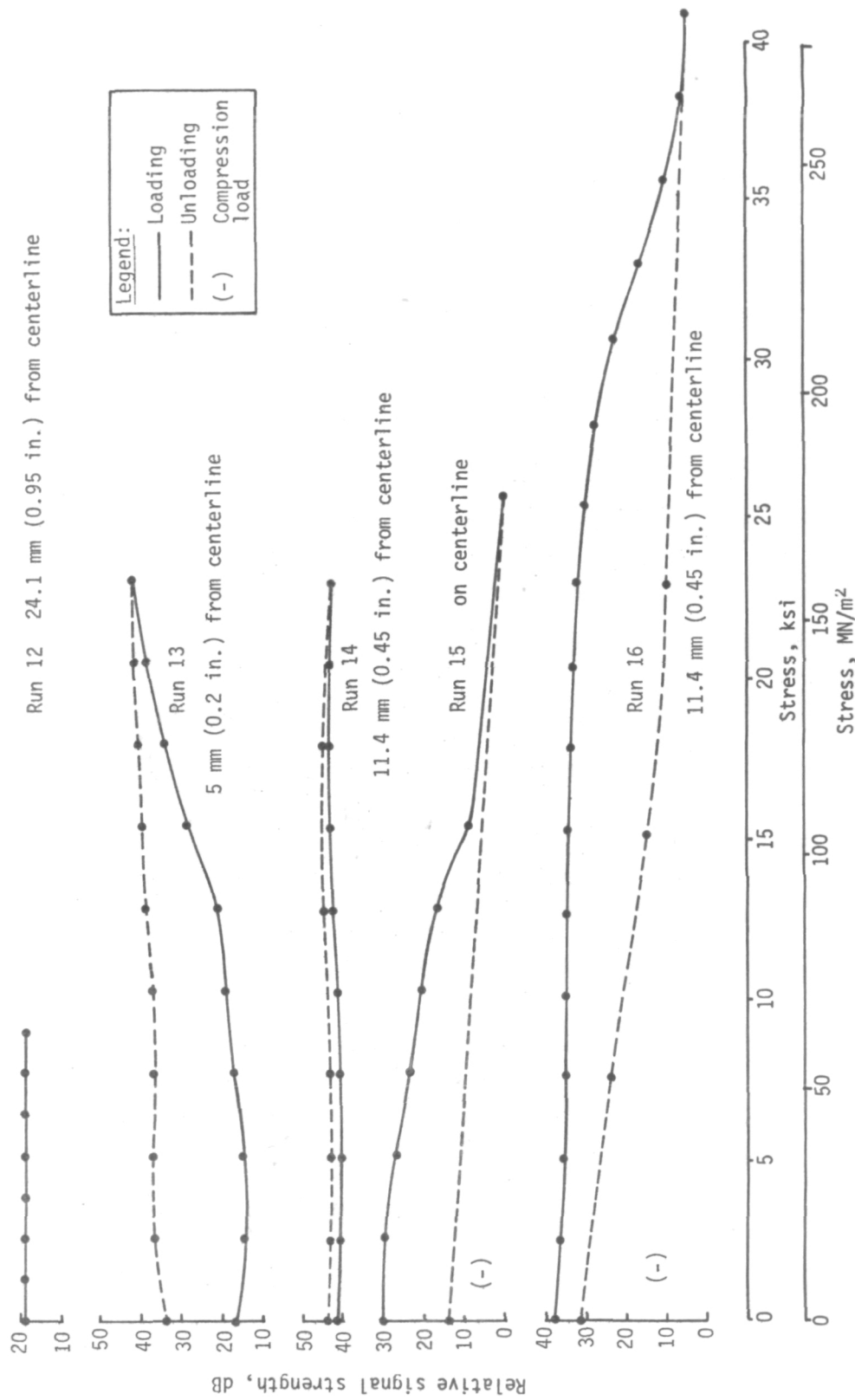


Figure 52. - Concluded.

a very tight flaw; initial signal strength was only ~ 8 dB. This specimen was evaluated in greater detail than the preceding specimens. Ultrasonic readings were taken along the width at various distances from the centerline:

Position	Distance from centerline	
	mm	(in.)
A	0	(0)
B	5.0	(0.20)
C	11.4	(0.45)
D	17.8	(0.70)
E	24.1	(0.95)

Initial readings showed that the crack was tightest at the centerline. Signal strength decreased from ~ 8 dB at position A to 16 dB at B and 32 dB at D. Ultrasonic signal strength measurements were made at positions A through E for various stress levels, as shown in figure 52. No attempt was made to use all combinations of stresses and locations. Tests conducted at position A for stresses up to 71 MN/m^2 (10 ksi) showed no evidence of crack opening. At position B, tension loading up to 160 MN/m^2 (23 ksi) failed to produce full opening, although the data suggested that full opening would probably occur at the next load increment. Readings taken at position C when loaded to 160 MN/m^2 (23 ksi) indicated full opening. Compressive loading to 285 MN/m^2 (41 ksi) failed to produce crack closure at C. At location E (beyond the end of the flaw), signal strength was low, indicating unimpeded transmission. The level was not as low as the indications given by the tight flaw, probably because scattering caused some reflection from the area at the end of the flaw.

A second specimen of the same nominal size (F-42) was evaluated with the axis of the ultrasonic beam at the centerline of the defect. The initial strength level (16.7 dB) was moderately low, and a stress of 160 MN/m^2 (23 ksi) was required to achieve full opening.

Figure 53 compares test results for all specimens (cylindrical and flat) on a plot of initial ultrasonic signal strength versus tensile stress required to cause full residual crack opening.

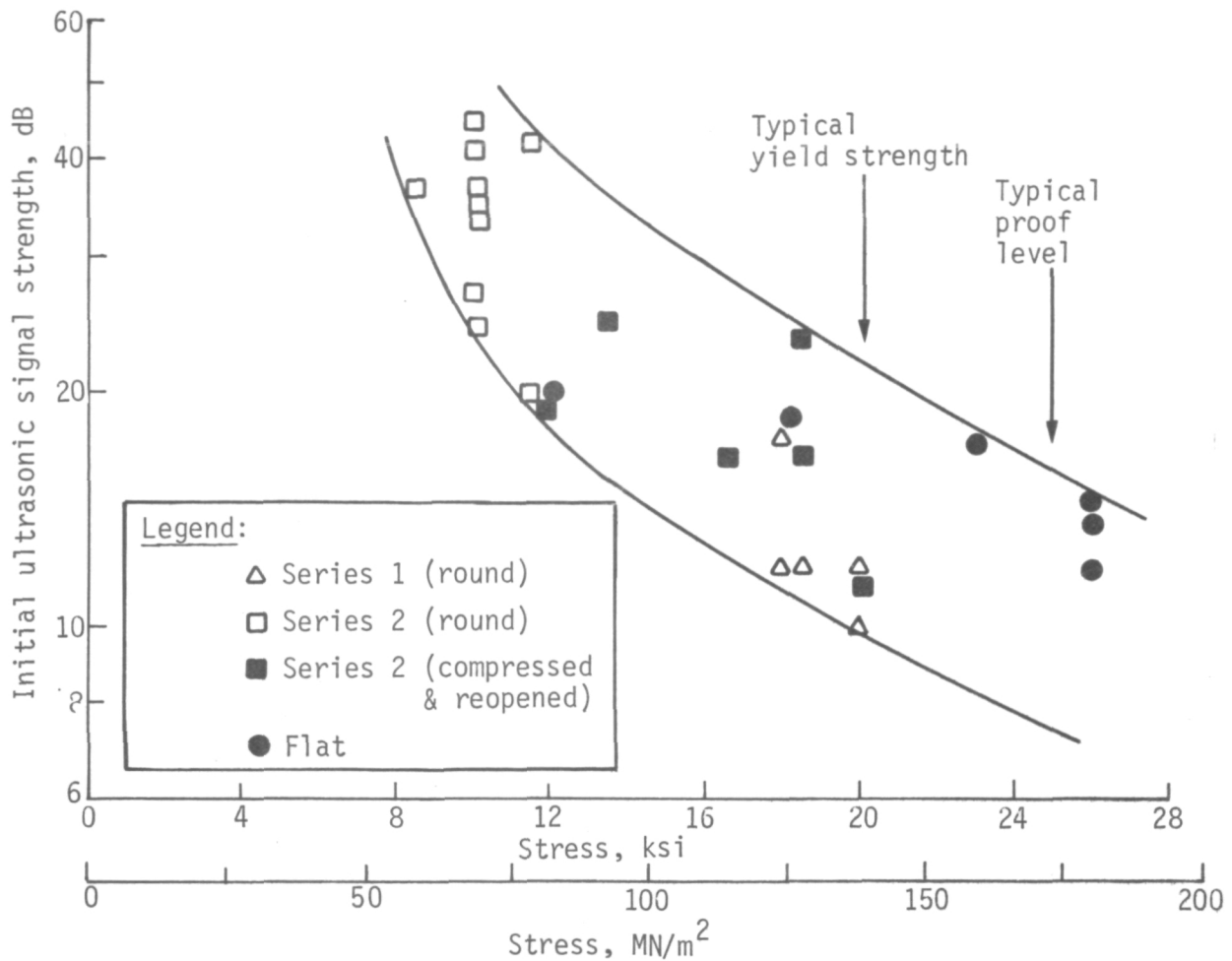


Figure 53. - Stress required to cause full opening of buried lack-of-fusion defects.

The stress required to cause opening varied inversely with initial ultrasonic signal strength. Data obtained from specimens that were opened then compressed to cause crack closure, and reopened, also followed the indicated trend. Initial ultrasonic strength is a function of residual compressive stress resulting from welding. For the round bar configuration, stresses approaching the yield stress range were required to develop the full crack opening necessary to enhance detectability. For the flat specimens, stresses above yield were required to develop full opening in some cases.

The flat specimens probably better typify the welding conditions in structural hardware and attendant residual compressive stresses than round specimens. According to the data shown in the figure, the commonly used proof stress level, approximately 175 MN/m² (25 ksi) should provide detection capability for most tight lack-of-fusion defects.

POSTLOAD CYCLIC CRACK GROWTH CHARACTERISTICS

The objective of this effort was to determine the growth characteristics of embedded lack-of-fusion defects (LFD) during cyclic loading after proof-test exposure. This chapter presents a detailed description of the ultrasonic technique with accompanying test data developed to demonstrate system performance and the crack growth characterization for LFD weldments.

Ultrasonic System Description and Representative Data

Figure 54 illustrates the scheme for ultrasonic flaw monitoring and mapping using a collimated beam for a surface-flawed specimen containing an initial crack starter in the form of a V-notch with a circular front. As the transducer assembly moved from right to left (along the semiminor axis of the flaw or its a direction), the received signal remained essentially constant. As the transducer assembly moved farther to the left, the reflected signal (dashed lines) became partially obscured by the tip of the initial crack starter (position B). At this point, movement of the transducer assembly to the left might be continued until the strength of the received signal was reduced to half the original value compared to position A. The reduction of the signal is illustrated on the scope screen. Figure 55 shows the actual appearance and clarity of resolution of a typical signal on the cathode-ray tube of the ultrasonic generator. The reflected beam was "split in half" in terms of the received signal strength. The coupling medium (deionized water) was barred from the crack cavity by a rubberized seal. As the crack extended in the a direction, more of the collimated beam would be obscured, reducing the strength of the received signal. To compensate for this reduction, the transducer assembly would have to be moved in the opposite direction (from left to right) until the strength of the received signal regained its previous value as seen at B. The new position for the extended crack front is shown at C. The relative distance between the two positions represents the amount of crack growth that occurred. The monitoring process could be continued until the crack grew through to the surface, as illustrated at D.

Figure 56 shows the transducer mounting system and traversing apparatus. The transducers were mounted so that the distance between them and the angular orientation could be adjusted. Traversing was accomplished by two micrometer slide assemblies. Figure 57 shows the assembled system in place in a test machine. The photograph shows a test specimen, immersion tank, and traversing assembly.

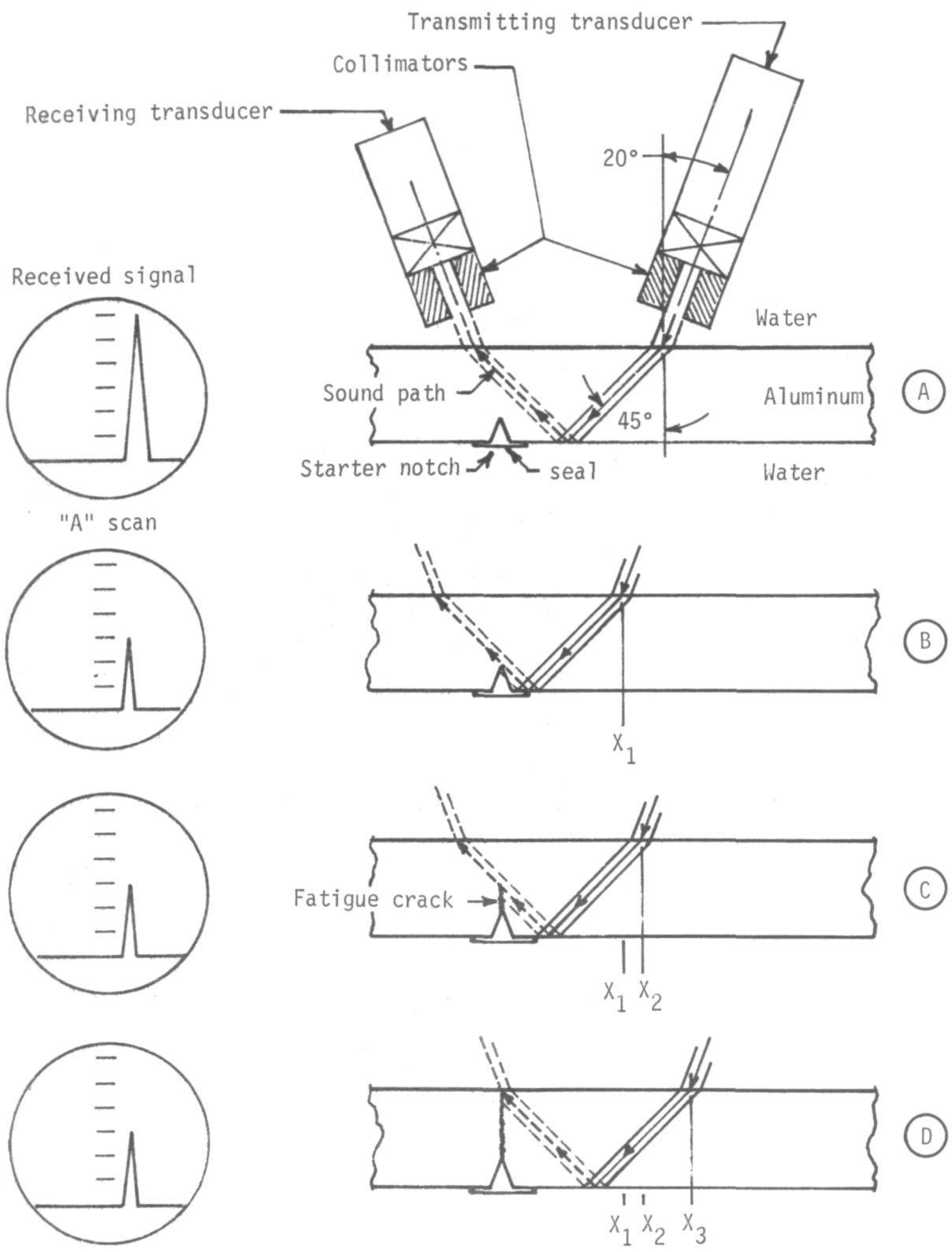


Figure 54. - Scheme for ultrasonic monitoring.



Figure 55. - Ultrasonic apparatus for generating and monitoring collimated beam.

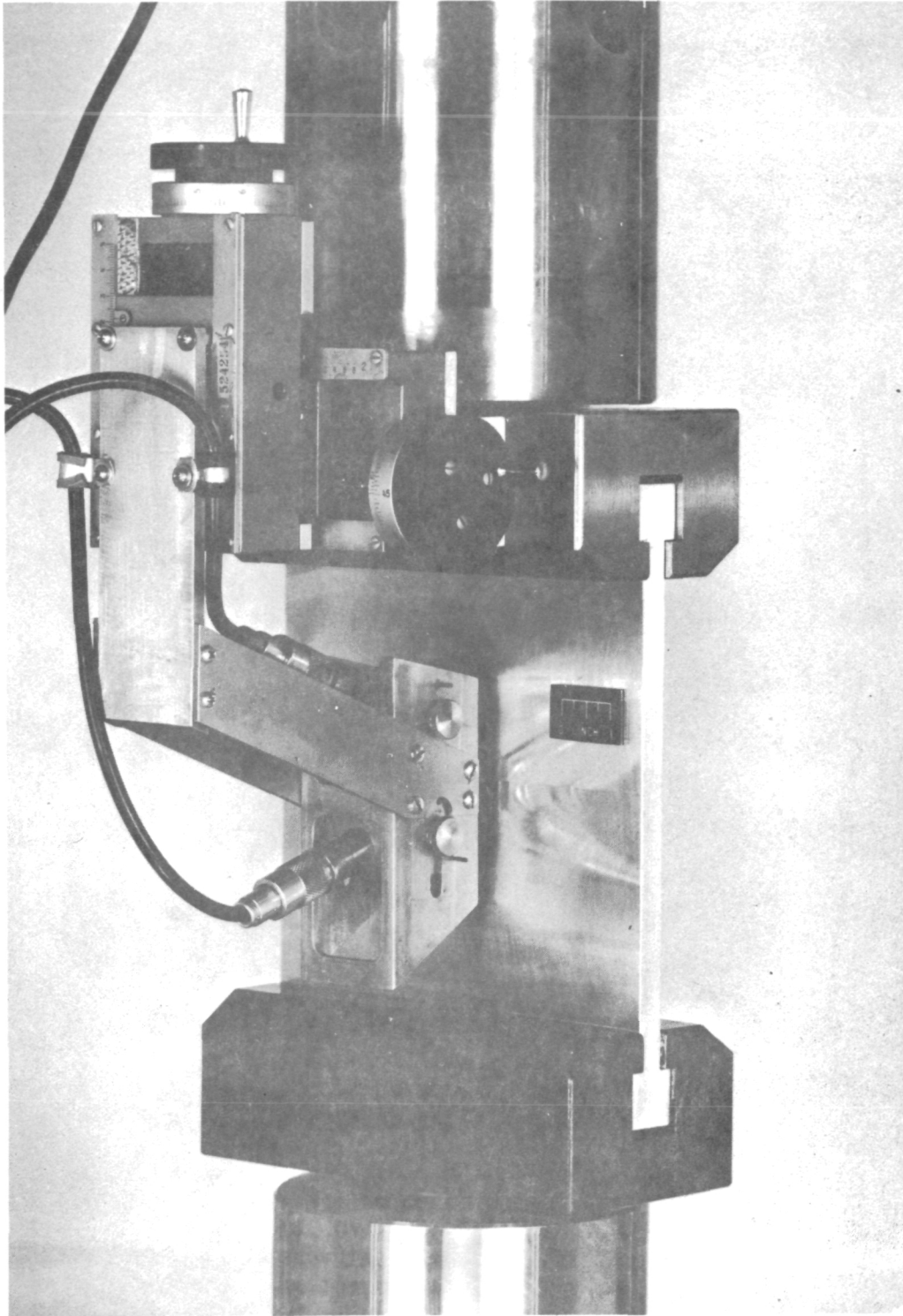


Figure 56. - Transducer mounting system and traversing apparatus.

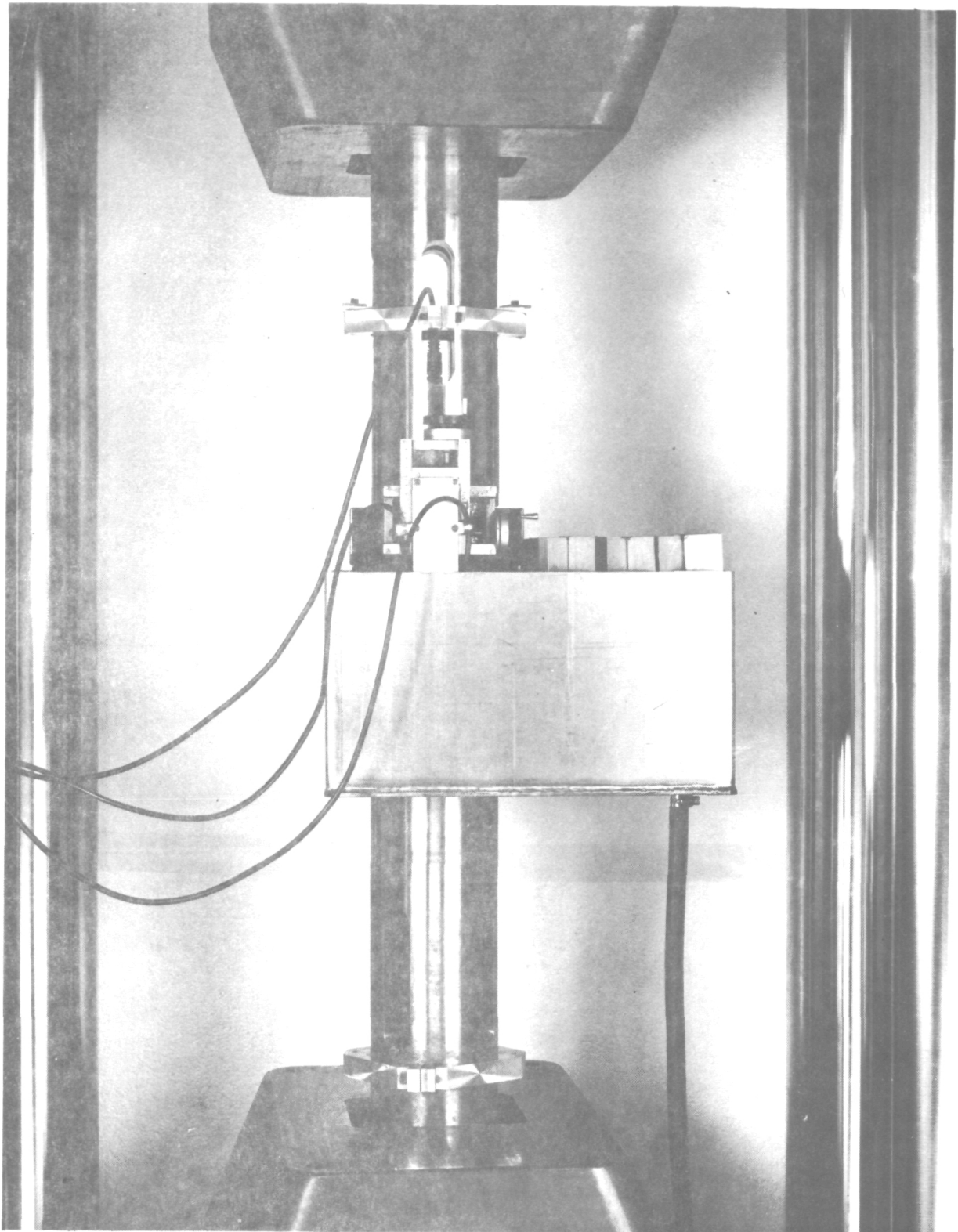


Figure 57. - Ultrasonic system with immersion tank installed in testing machine.

The apparatus used for generation and monitoring of the ultrasonic signal was a Sonatest UFD 1 (fig. 55), 5-MHz zirconate titanate 8.7-mm (0.25-in.) diameter transmitting transducer and a lithium-sulfate receiving transducer of matching frequency and size. Transmitting and receiving transducers were adjusted for an incident and reflected angle of 20° , which produces an incident and reflected shear beam of 45° in water. That incident angle was chosen because it provided a one-to-one correspondence between surface travel and crack depth. The two transducers were laterally positioned to pick the first reflection from the back surface of the specimen. This position was determined by the thickness of the specimen and distance between the transducer and specimen surface. The two transducers were then locked in place and attached to the traversing assembly. The transmitted and received beams were collimated to a 3.2-mm (0.125-in.) diameter.

Preliminary tests were performed to establish the potential of the apparatus to detect crack front location for flaw growth determination and mapping flaw size and shape. The following paragraphs describe the results of these tests.

Tests conducted on material that produced a very smooth fracture face (2219-T87 aluminum weldment) and a rough, highly delaminated fracture face (7007-T6 aluminum base metal) showed that the signal was not affected by fracture face characteristics.

Crack growth in three representative specimens (one of welded 2219 and two of parent metal 7007 alloy) was monitored ultrasonically. Each specimen contained an initial crack starter 3.2 mm (0.125 in.) deep and approximately 2.5 mm (1.0 in.) long on the surface.

All specimens were 1.3 cm (0.5 in.) thick and 13 cm (5 in.) wide in the gage area. Specimens were mounted in the fixture, the crack opening was sealed, and, for compressive loading, provided with a set of buckling restraint panels.

The 2219 aluminum weldment specimen was subjected to cyclic loading at a stress of 110 MN/m^2 (16 ksi) for 10 000 cycles. The ultrasonic probe was then installed to monitor crack progression as a function of cyclic loading and overload sequences. The point of maximum crack depth was monitored. A plot of ultrasonic crack growth data (fig. 58) clearly shows that the system is sensitive to detection of very subtle changes in crack growth behavior. Cyclic testing was performed to generate a curve of steady crack growth versus cycles. Cycling continued until the crack front approached the midposition of the material thickness. At 14 810 cycles, the test was interrupted because of accidental overheating of the hydraulic oil. The specimen load dropped to zero. After about 10 minutes delay to cool the oil, the machine and cyclic testing resumed.

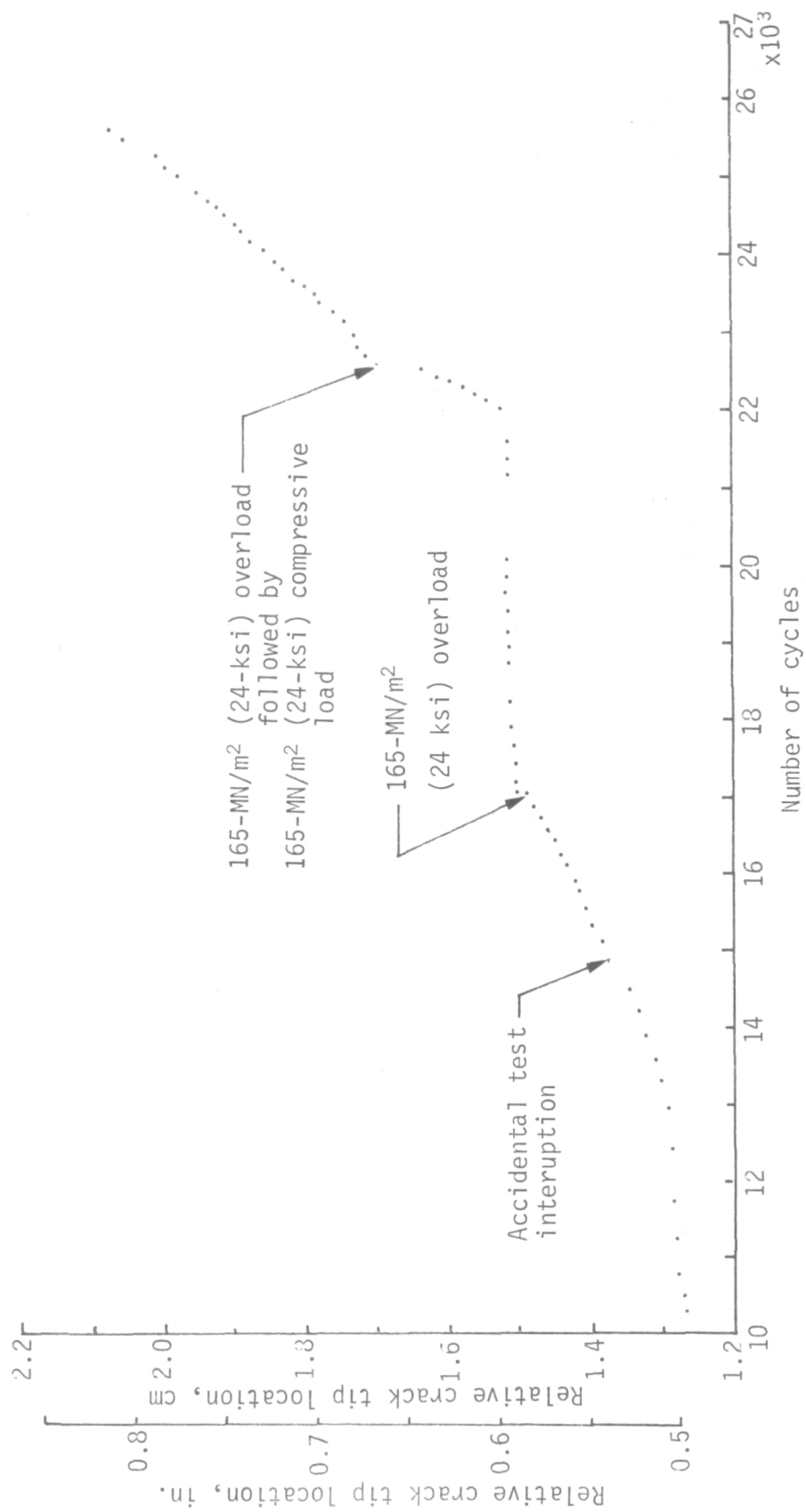


Figure 58. - Plot of ultrasonic crack growth data for 2219-T87 aluminum alloy weldment.

The next crack-front readout at 14 890 cycles showed an increase in growth, suggesting that 10 minutes at zero load relaxed the resistance to crack propagation behavior similar to that observed after an underload. As cyclic testing continued, the momentary effect of the underload quickly disappeared, and crack growth resumed its previous rate. The slopes of the curve before and after the loss of power showed similar contours. After 17 050 cycles, the test was interrupted, the specimen unloaded to near zero load, then reloaded to a 110-MN/m^2 (16-ksi) stress to map the crack front using the collimated ultrasonic beam technique. After mapping, the load was increased to 165 MN/m^2 (24 ksi), stabilized for about 1 minute, then unloaded to 110 MN/m^2 (16 ksi) and mapped again. Figure 59 shows the crack front contour before and after the overload. As seen in figure 58, the effect of the overload manifested itself in the immediate arrest of crack growth.

A very small increase in growth was noted as the number of cycles approached 18 000, and there was virtually no growth to 22 000 cycles. Readings were taken while cyclic testing continued for the next 500 cycles. Crack growth rate was very high, and it was decided to subject the specimen to an overload followed by a compressive load of the same magnitude. In another specimen, a single overload at this point resulted in another delay of cyclic growth. Therefore, it appeared desirable to reverse the load from a tensile overload to a compressive underload of the same magnitude. This was done at the end of 22 560 cycles.

As in the previous case, cyclic testing was stopped, the load dropped to near zero then increased to 110 MN/m^2 (24 ksi) to map the crack front. The specimen was then overloaded to 65 MN/m^2 (24 ksi), allowed to stabilize for about 1 minute, then unloaded to 110 MN/m^2 (16 ksi) and mapped again. Note that the slow growth extension during the second overload was about the same as that during the first overload. The specimen was then completely unloaded and subjected to a compressive load of 165 MN/m^2 (24 ksi), held for a period of about 1 minute at the maximum compressive load, then unloaded to zero load. Figure 60 shows the crack-front contour before and after the second overload.

Resumption of cyclic testing at the 110-MN/m^2 (16-ksi) stress showed a linear increase in crack growth until breakthrough to the back surface at 25 600 cycles. Crack growth rate was less than it was before the second overload cycle. Figure 61 is a fractograph of the fractured specimen after testing.

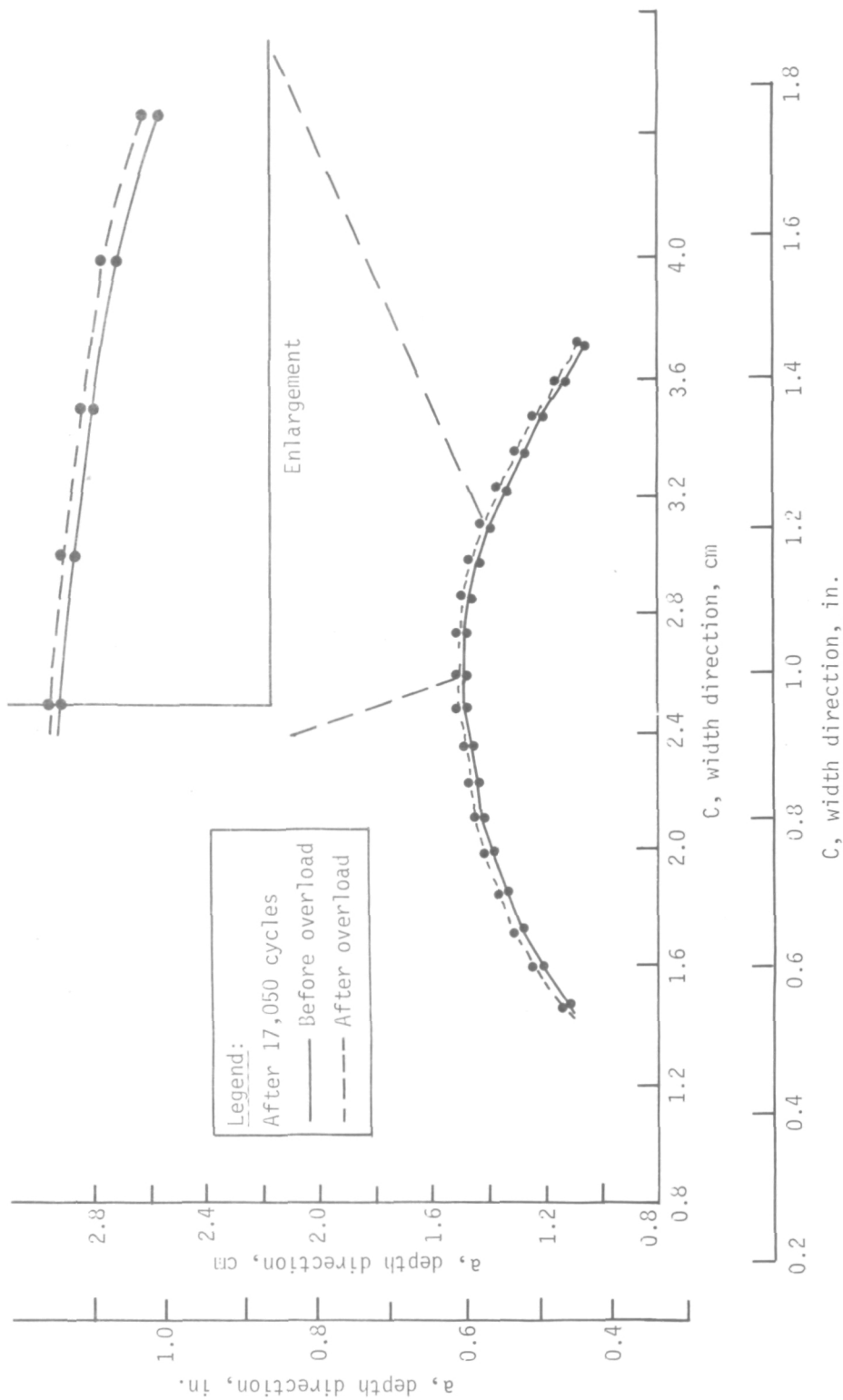


Figure 59. - Crack front of 2219-T87 aluminum alloy weldment before and after first overload as mapped by ultrasonic technique.

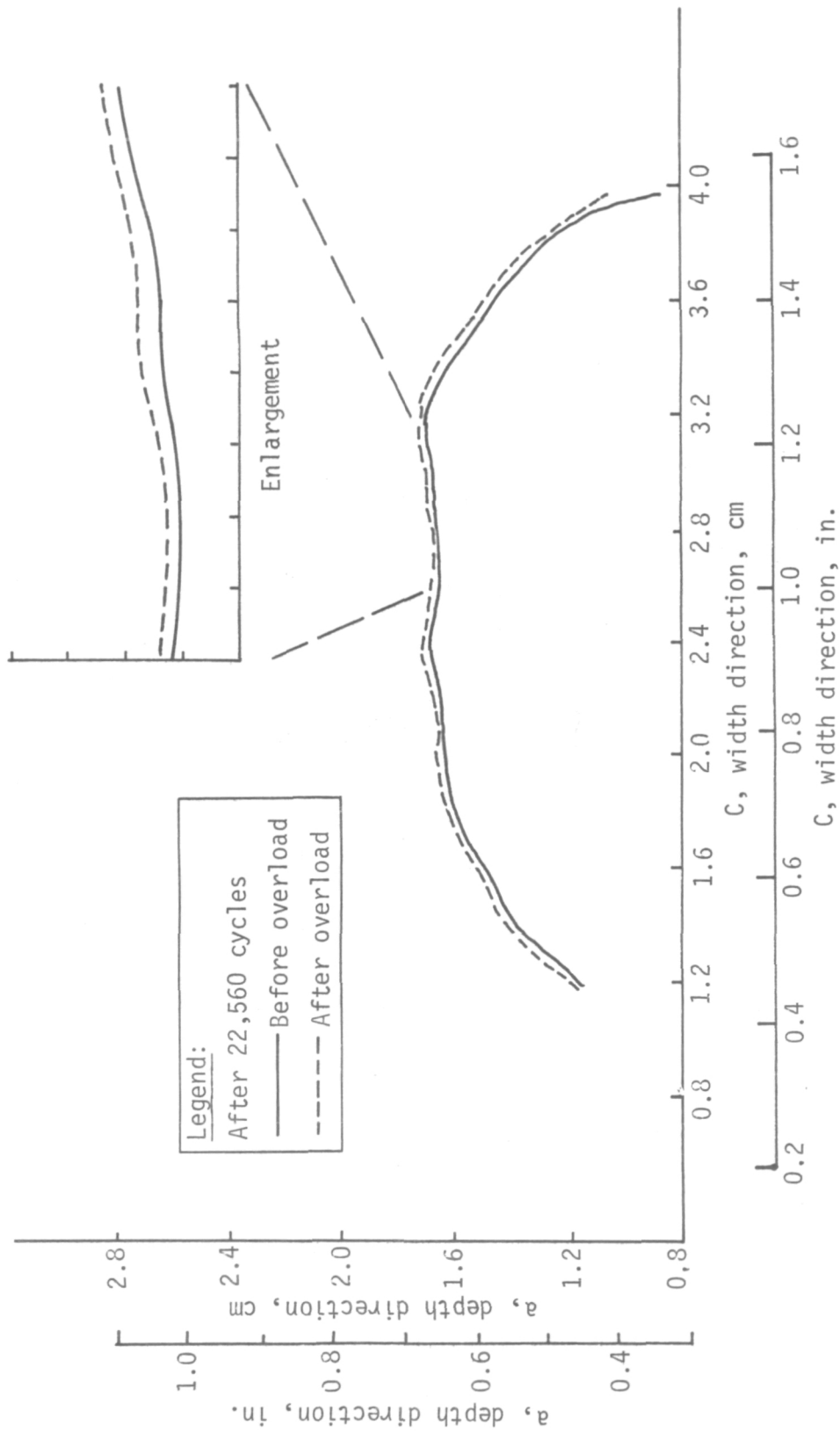


Figure 60. - Crack front of 2219-T87 aluminum alloy weldment before and after second overload as mapped by ultrasonic technique.

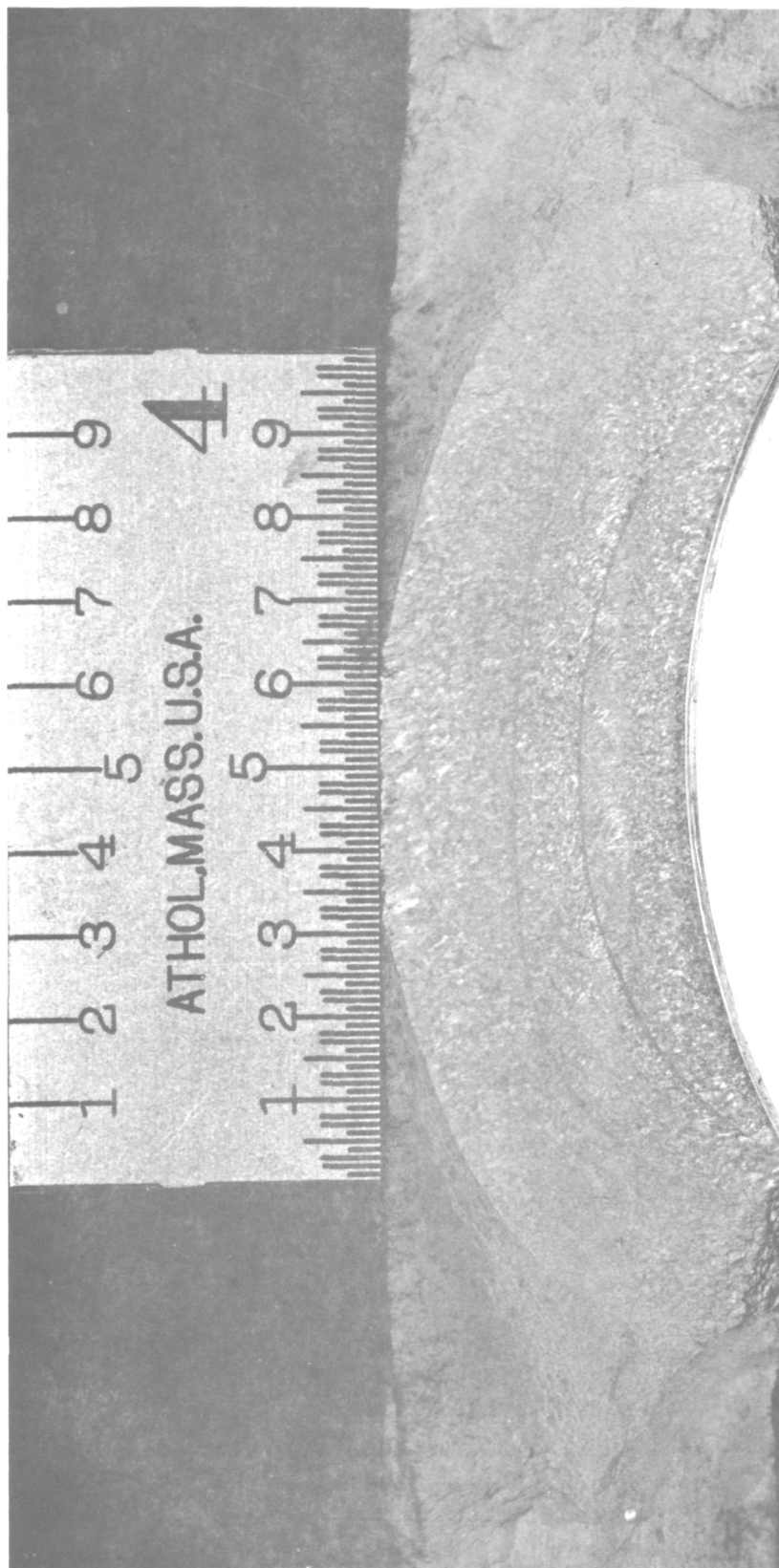


Figure 61. - Fractograph of 2219 aluminum weldment.

The 7007-T6 aluminum base-metal specimens were tested in a similar manner. Figure 62 is graphic record of the first specimen. Cyclic testing started at a stress of 138 MN/m^2 (20 ksi). Crack growth rate appeared to be excessively high. At the end of 930 cycles, cyclic testing was interrupted, and the cyclic stress level was lowered to 110 MN/m^2 (16 ksi). Crack growth resumed after about 2000 cycles and proceeded nonuniformly until 1000 cycles were reached. The crack growth rate was greater from 3000 to 5000 cycles than it was from 5000 to 10 000 cycles. This unusual behavior may have been caused by the delamination tendency of this alloy.

After 1000 cycles, the specimen was overloaded to 165 MN/m^2 (24 ksi) and cycling was then continued. The resulting retardation appeared for approximately 500 cycles and growth resumed. At 14 000 cycles, a second overload cycle was applied. This overload was significantly higher [220 MN/m^2 (32 ksi)] and resulted in an extremely long retardation period (13 000 cycles). This long retardation period could have been caused by a large plastic zone because of the higher stress, the close proximity of the back surface, formation of a delamination, or all three. After 27 000 cycles, crack growth resumed and the crack grew to back-surface breakthrough at almost 32 000 cycles.

The specimen was pulled to failure and revealed an extremely rough fracture face with numerous delaminations and poorly defined outlines of the various loading histories. Figure 63 shows the fracture face illuminated in two manners to illustrate the fracture surface roughness (oblique light) and growth bands (direct illumination).

The second 7007-T6 aluminum specimen was tested under the same conditions as the first except that, after the second overload, a 220-MN/m^2 (32-ksi) compressive load was applied. Figure 64 presents the cyclic crack-growth data record.

The first overload [165 MN/m^2 (24 ksi)] produced a small retardation, as noted in the first specimen. The second overload series (tension followed by compression) resulted in a very short retardation, then resumption of crack growth. Figure 65 shows fracture face views of this specimen.

Cyclic Crack Growth Data

Round specimens. - The round bar specimens were cyclically evaluated before development of the flaw mapping technique. Attempts were made to determine whether growth was detectable using the ultrasonic transducers on the specimen axis of symmetry. The defects were too large for the relatively small core of the

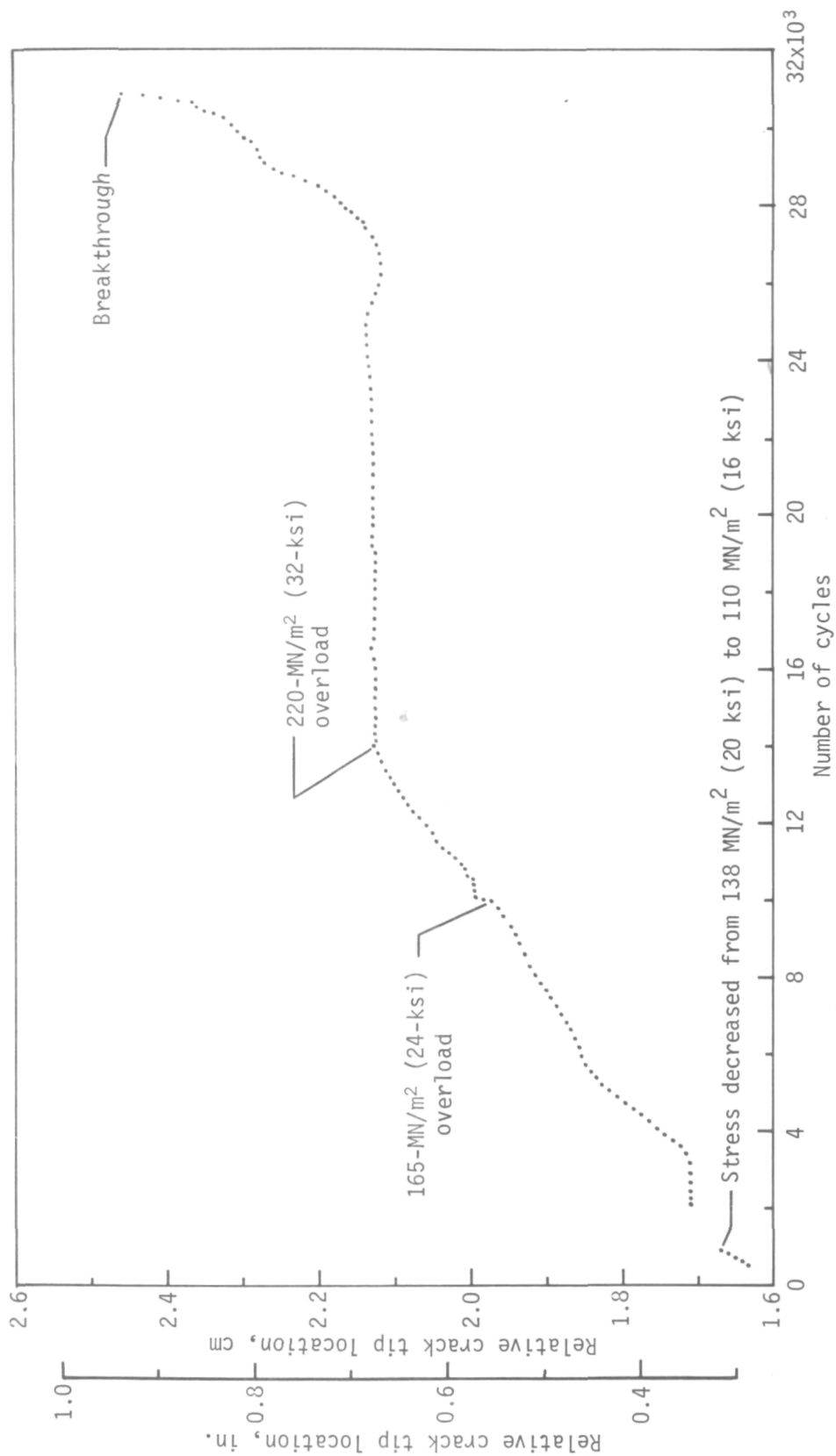
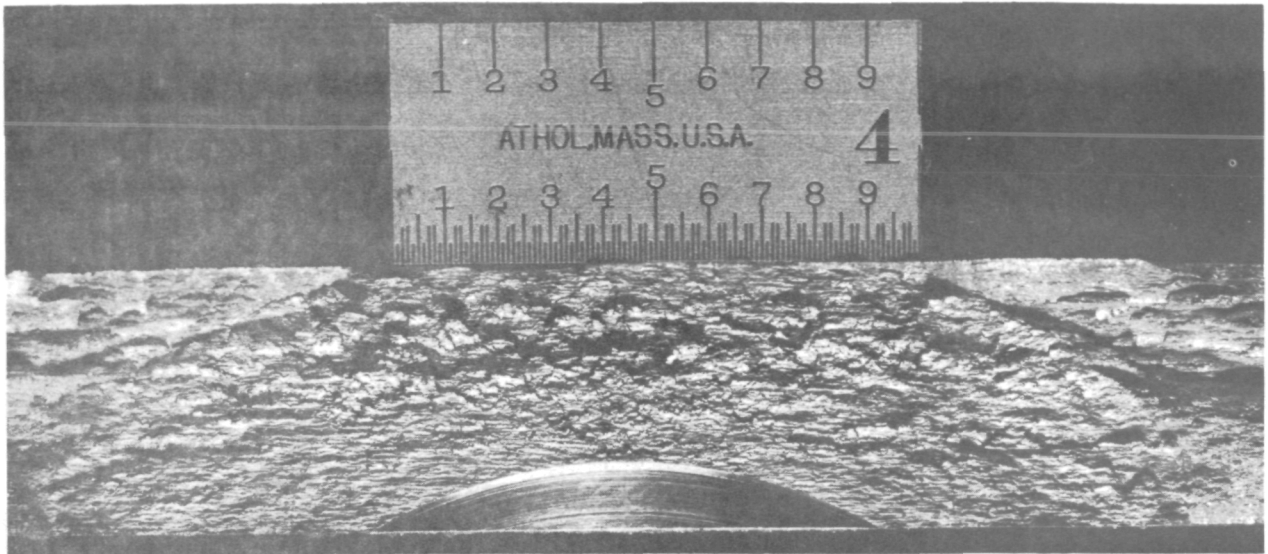
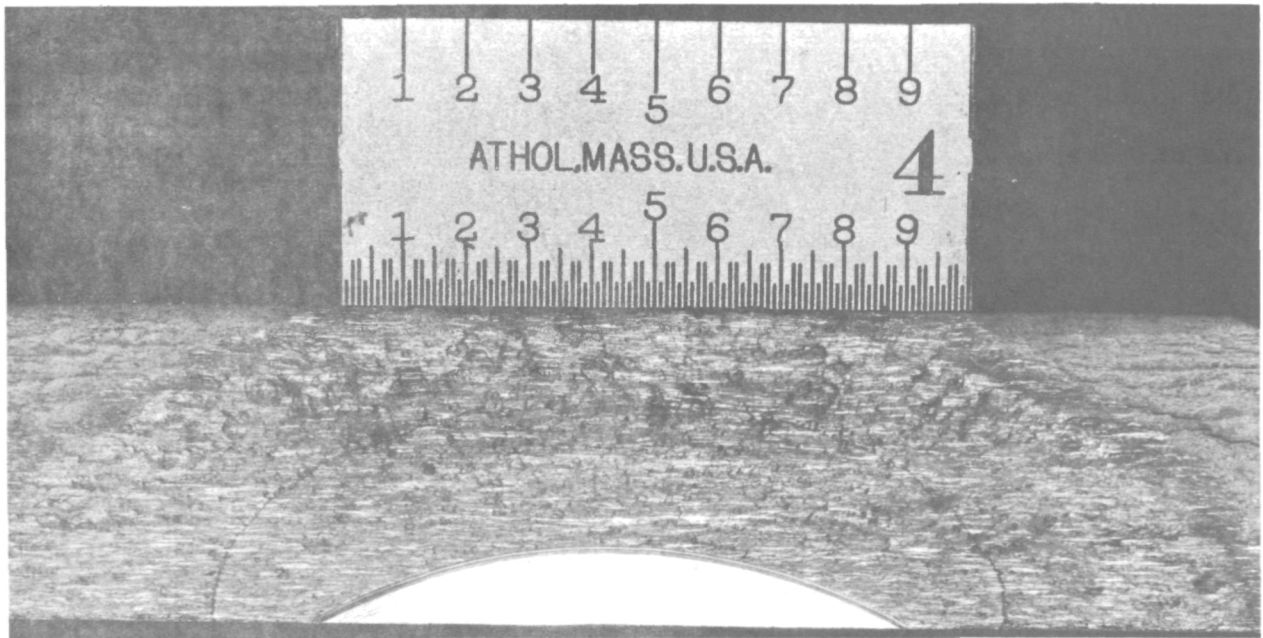


Figure 62. - Plot of ultrasonic crack-growth data for 7007-T6 aluminum-alloy parent-metal specimen 1.



Oblique illumination



Direct illumination

Figure 63. - Fracture-face views of 7007-T6 aluminum-alloy specimen 1.

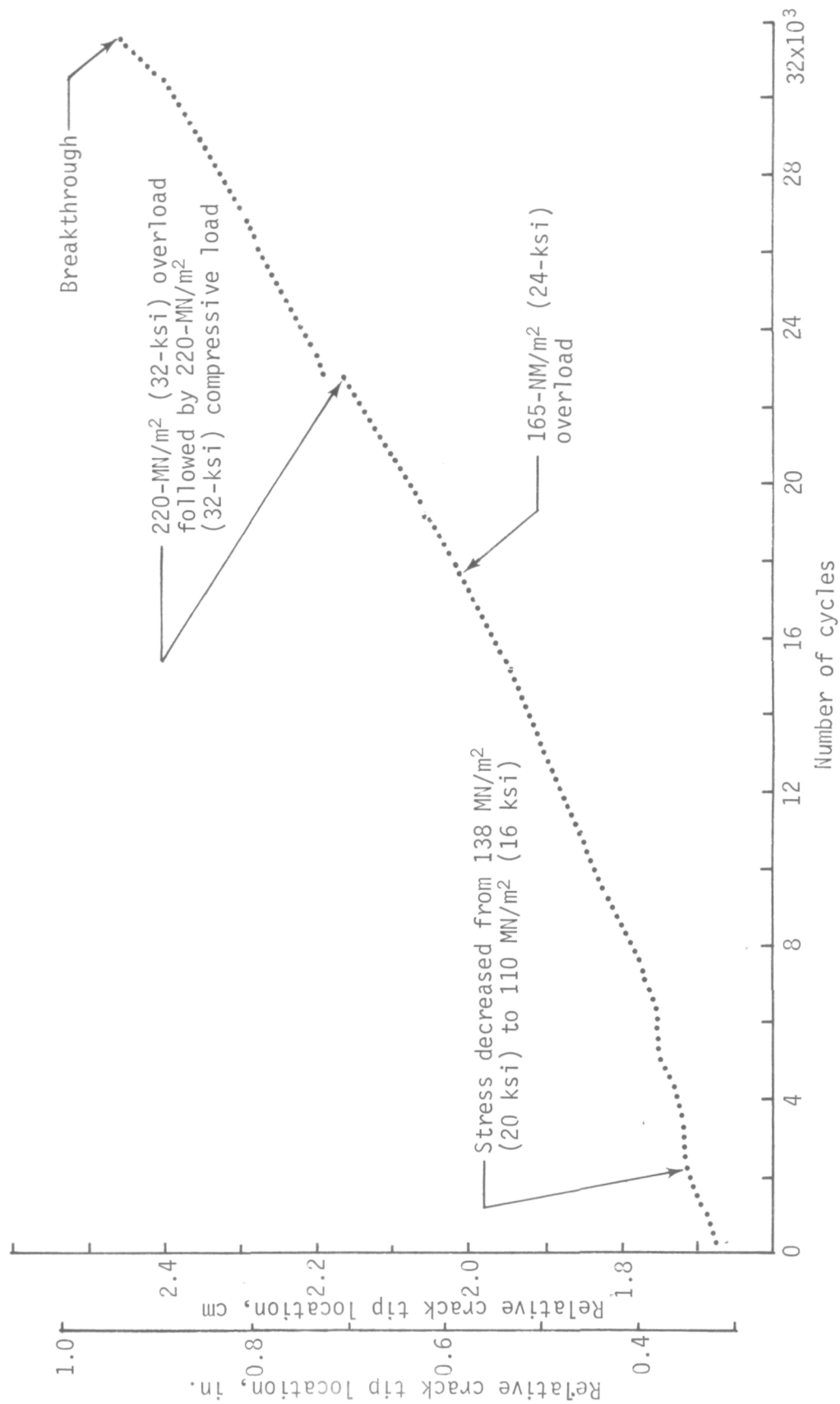
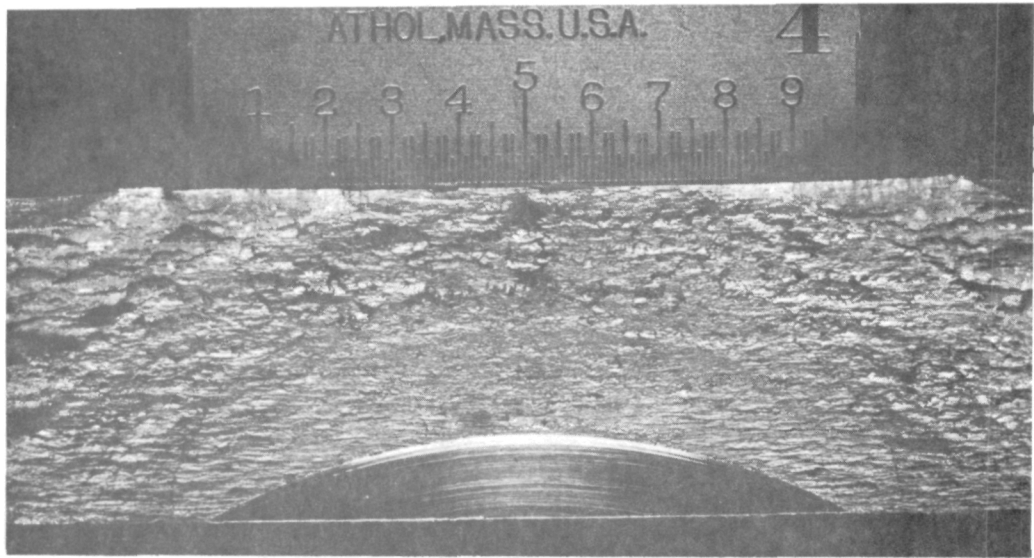
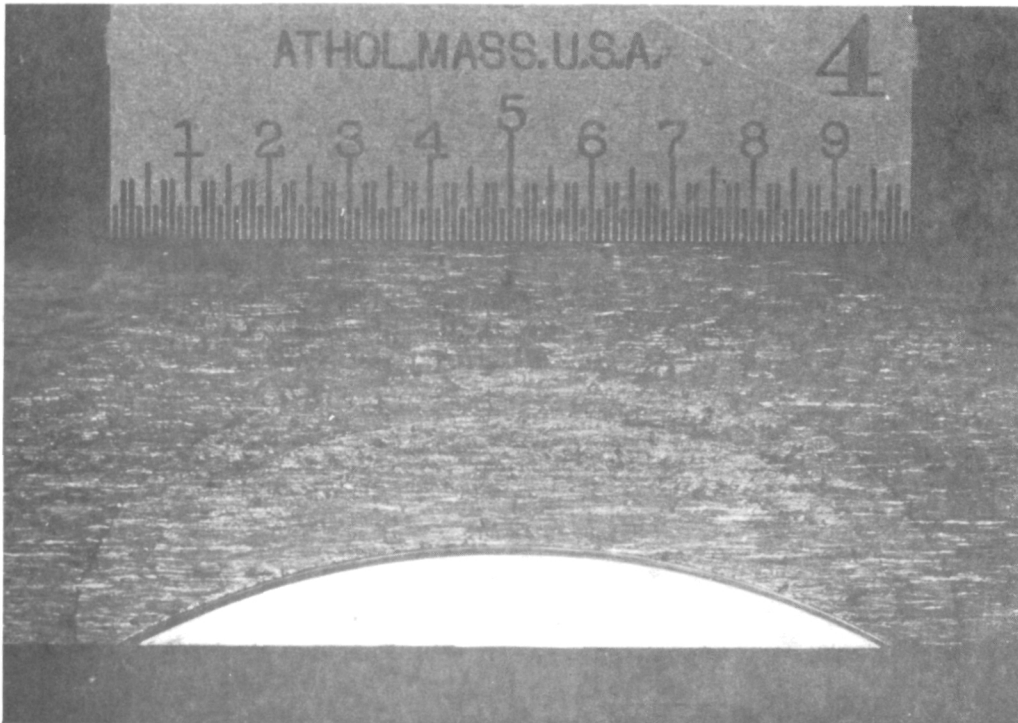


Figure 64. - Plot of ultrasonic crack growth data for 7007-T6 aluminum-alloy parent metal, specimen 2.



Oblique illumination



Direct illumination

Figure 65. - Fracture-face views of 7007-T6 aluminum alloy specimen 2.

ultrasonic beam to quantify growth. A study of the signal strength reflected from flat-bottomed holes of various sizes showed that the ultrasonic technique was quite insensitive for holes exceeding the beam diameter of 9.5 mm (3/8 in.) (fig. 66).

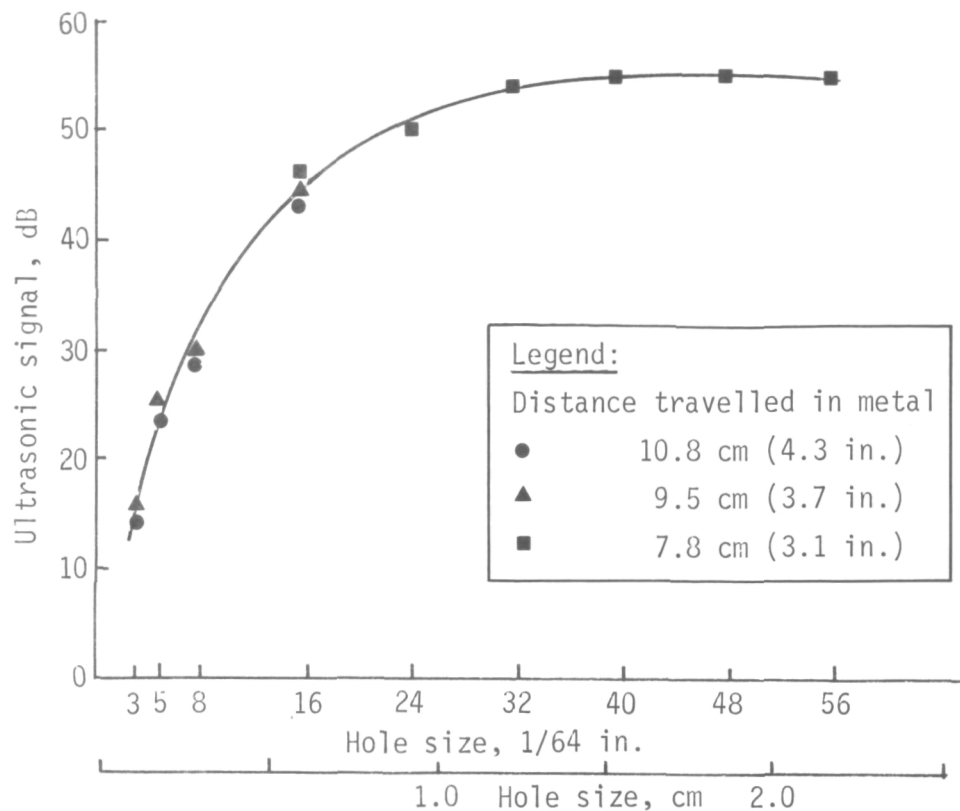


Figure 66. - Relative ultrasonic signal strength reflected from flat-bottomed holes.

In the absence of a crack-growth monitoring technique, specimens were cycled with periodic fatigue band marking, then fractured. Growth data were obtained by direct measurement on fracture-face photographs using the planimeter technique previously described.

Table XVI summarizes data obtained from the round bar specimens. Figure 67 is a graphic presentation of the data. Comparative data for welded joints of the same thickness are relatively scarce; however, data for two thinner gages have been reported by Boeing (ref. 2) and are included in the data plot.

Flat specimens. - Three types of data were obtained:

- 1) cycles to breakthrough;
- 2) crack length versus N;
- 3) flaw mapping.

TABLE XVI. - CYCLIC GROWTH DATA FOR ROUND BAR SPECIMENS

Specimen no.	Crack size, a,		Stress, MN/m ² (ksi)	Maximum stress intensity, MN/m ^{3/2} , ksi √in.)	Number of cycles, N	Crack growth rate, da/dN, (μin./cycles)		Remarks
	Initial mm (in.)	Final mm (in.)				mm/cycle		
R-6	4.78 (0.188)	---	116 (16.8)	14.2 (12.9)	30 280	---		Failed during cycling
R-7	1.98 (0.078)	2.41 (0.095)	116 (16.8)	9.1 (8.3)	70 000	6.1 (0.24)		
R-9	2.41 (0.095)	4.70 (0.185)	153 (22.2)	13.3 (12.1)	48 500	47.0 (1.85)		
	5.05 (0.199)	6.91 (0.272)	130 (18.8)	16.3 (14.8)	25 000	74.2 (2.92)		
R-11	4.72 (0.186)	5.21 (0.205)	130 (18.8)	15.4 (14.0)	25 000	19.3 (0.76)		
R-13	3.20 (0.126)	3.78 (0.149)	130 (18.8)	13.0 (11.8)	60 000	9.7 (0.38)		
R-14	1.88 (0.074)	2.21 (0.087)	163 (23.6)	12.5 (11.4)	20 000	16.5 (0.65)		
R-15	2.92 (0.115)	3.52 (0.139)	163 (23.6)	15.6 (14.2)	38 550	15.7 (0.62)		
R-16	5.03 (0.198)	5.21 (0.205)	116 (16.8)	14.5 (13.2)	20 000	8.9 (0.35)		
R-18	3.30 (0.130)	3.30 (0.130)	46 (6.7)	4.7 (4.3)	400 000	0 (0)		
R-19	2.16 (0.085)	3.81 (0.150)	116 (16.8)	9.4 (8.6)	500 000	3.3 (0.13)		
R-20	3.81 (0.150)	8.13 (0.320)	163 (23.6)	17.9 (16.3)	5 000	1092 (43)		
	2.51 (0.099)	3.61 (0.142)	127 (18.5)	11.3 (10.3)	83 100	13.2 (0.52)		
R-21	3.61 (0.142)	4.37 (0.172)	151 (21.9)	16.4 (14.9)	3 500	218 (8.5)		
	4.04 (0.159)	4.83 (0.190)	93 (13.5)	10.4 (9.5)	170 000	4.6 (0.18)		
R-22	4.83 (0.190)	5.00 (0.197)	116 (16.8)	14.3 (13.0)	4 000	44.5 (1.75)		
	5.18 (0.204)	5.51 (0.217)	139 (20.2)	17.8 (16.2)	2 000	165 (6.5)		
R-23	4.72 (0.186)	5.46 (0.215)	70 (10.1)	8.5 (7.7)	800 000	0.9 (0.036)		
R-29	3.28 (0.129)	3.56 (0.140)	93 (13.5)	9.4 (8.6)	175 000	1.6 (0.063)		
	3.56 (0.140)	4.01 (0.158)	116 (16.8)	12.2 (11.1)	40 000	11.4 (0.45)		
R-30	4.09 (0.161)	5.23 (0.206)	139 (20.2)	15.7 (14.3)	5 600	206 (8.1)		
	2.67 (0.105)	4.32 (0.170)	93 (13.5)	8.4 (7.6)	250 000	6.6 (0.26)		
R-30	4.32 (0.170)	5.77 (0.227)	116 (16.8)	13.5 (12.3)	48 000	30.2 (1.19)		
	8.69 (0.342)	12.2 (0.480)	93 (13.5)	15.4 (14.0)	135 000	25.9 (1.02)		
	12.2 (0.480)	16.0 (0.630)	116 (16.8)	22.6 (20.6)	3 170	1201 (47.3)	Failed during cycling	

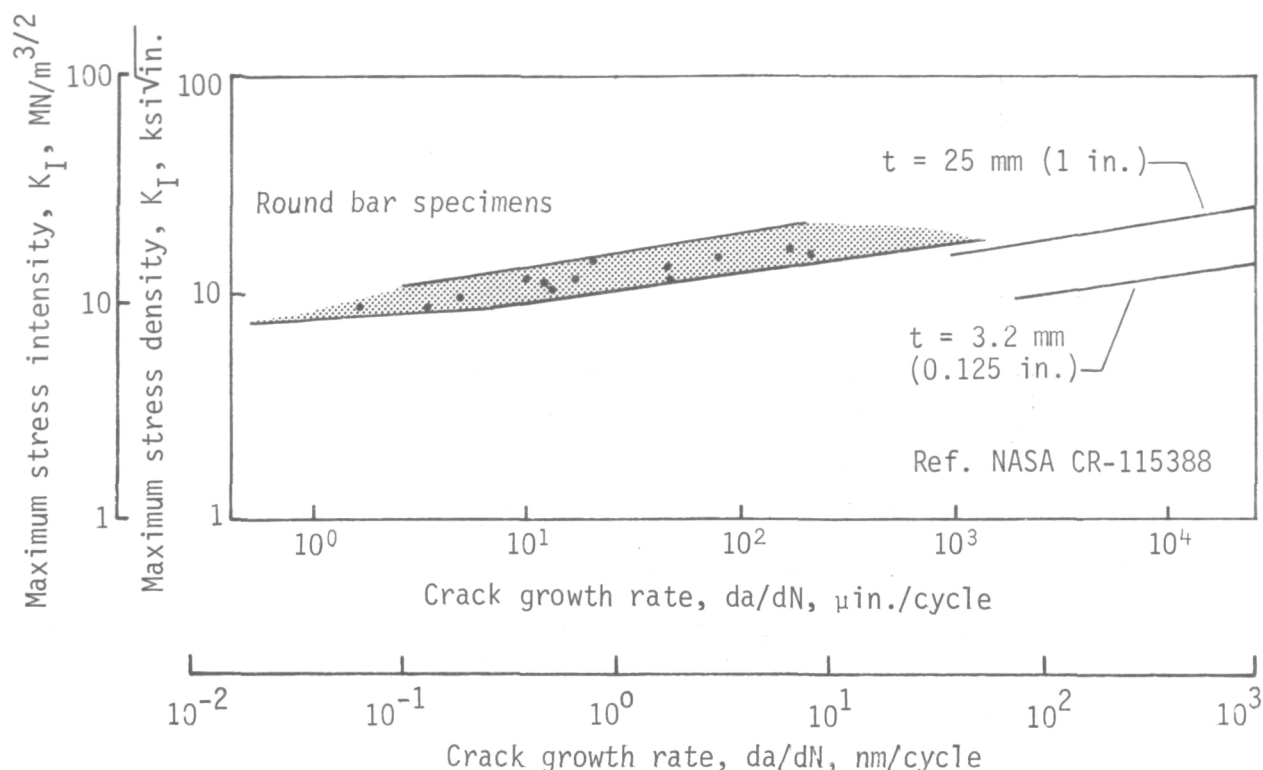


Figure 67. - Cyclic crack growth data for round bar specimens.

Thirteen specimens were cycled to determine the number of cycles required to cause fracture of the ligament. Many of these specimens had been used to provide residual crack-opening data, and were therefore subjected to varying levels of loading before cycling. The levels varied from less than to significantly more than that used for cycling. Such variables might affect crack growth behavior because of the nonuniform relief of residual stresses and the varying tightness of the defects. Figure 68 shows the test data in graphic form. Ligament thickness is plotted against the number of cycles to cause breakthrough. Ligament thickness was measured on the fracture face as the actual distance traversed in the region where the crack grew to the surface. Because the as-welded crack front was generally not uniform, the measurement is an average value. Data representing tests in which the prestress exceeded the cyclic stress are shown as diamonds; data for tests in which the prestress did not exceed the cyclic level are shown as circles. The data generally show that cycles required to penetrate the thickness increase with increasing ligament size and decreasing stress. These data show that, for ligaments of approximately 2 to 4 mm (0.08 to 0.16 in.) and stress at or slightly below the weld yield strength, the cyclic life varies generally in the range of 10^3 to 10^4 cycles. Table XVII summarizes available data.

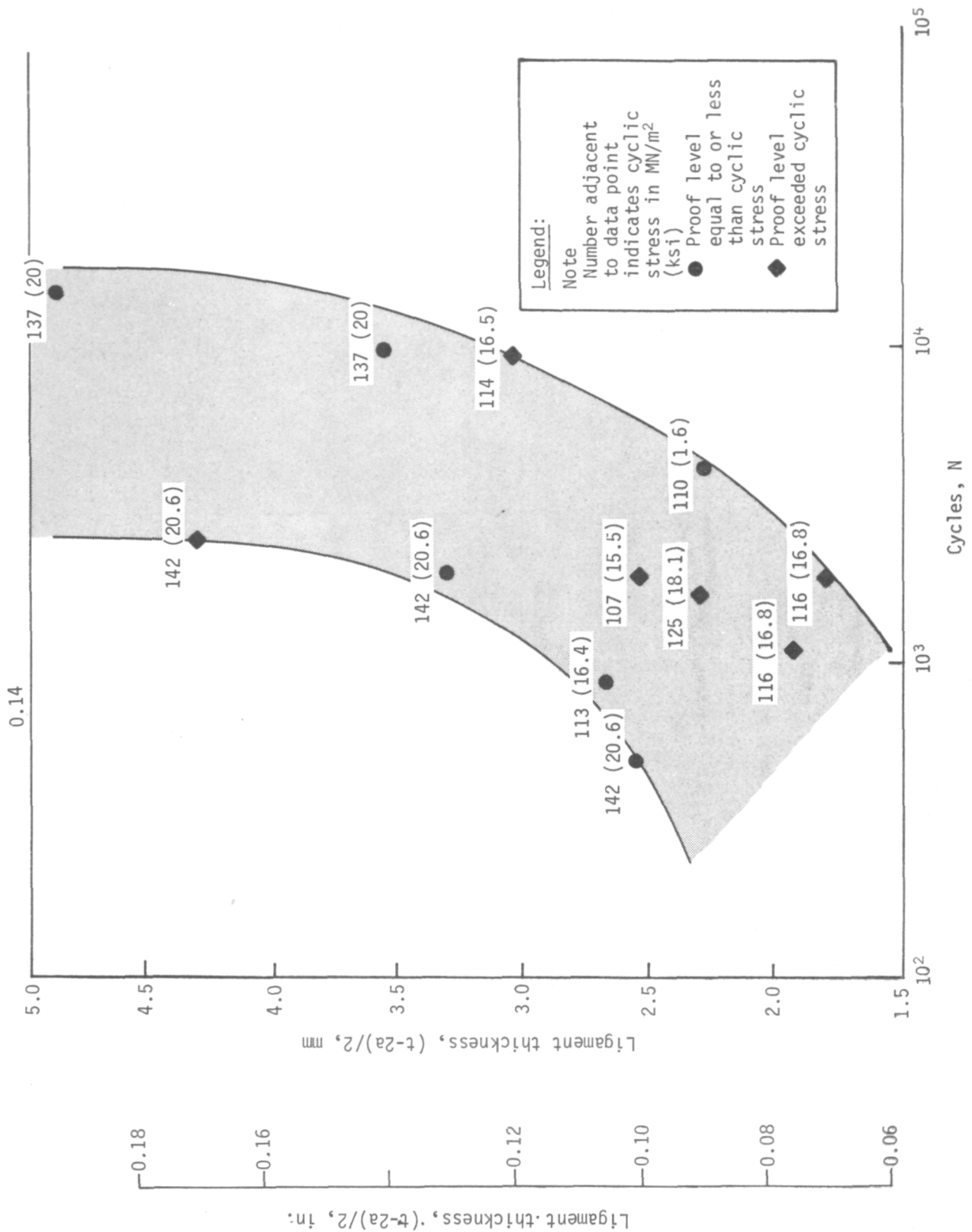


Figure 68. - Ligament breakthrough data.

TABLE XVII. - LIGAMENT PENETRATION DATA FOR FLAT SPECIMENS

Specimen no.	Proof stress,		Cyclic stress,		Cycles to breakthrough, N	Ligament thickness, (t-2a)/2	
	MN/m ²	(ksi)	MN/n ²	(ksi)		cm	(in.)
F-1	89	(72.9)	142	(20.6)	13 890 (disc)	0.48	(0.19)
F-2	178	(25.8)	142	(20.6)	22 400	0.43	(0.17)
F-3	107	(15.5)	142	(20.6)	20 000	0.33	(0.13)
F-12	178	(25.8)	107	(15.5)	75 000	0.30	(0.12)
F-13	138	(20.0)	138	(20.0)	98 300	0.36	(0.14)
F-15	125	(18.1)	134	(19.4)	8 400	0.28	(0.11)
F-21	142	(20.6)	142	(20.6)	4 800	0.25	(0.10)
F-22	160	(23.2)	125	(18.1)	12 300	0.28	(0.11)
F-23	214	(31.0)	125	(18.1)	16 700	0.23	(0.09)
F-24	110	(16.0)	110	(16.0)	41 000	0.23	(0.09)
F-30	160	(23.2)	116	(16.8)	10 700	0.20	(0.08)
F-35	160	(23.2)	116	(16.8)	18 200	0.18	(0.07)
F-42	160	(23.2)	107	(15.5)	18 400	0.25	(0.10)

Five specimens were ultrasonically monitored to provide data for a versus N by first locating the semiminor axis of the surface flaw, then the periphery of the flaw on that axis. The specimen was then cyclically loaded to provide crack extension. The semiminor axis was then traversed to locate the crack front. Figure 69 summarizes crack-growth results obtained from the curves of a versus N. These data agree relatively well with the results presented for cylindrical bar specimens (fig. 67). Figure 70 presents the curves that give data for a versus N for the five specimens.

The major activity undertaken in this task was actual mapping of buried flaws in welded flat panels. The following paragraphs discuss the results of the flaw mapping.

At least one specimen of each of the five defect size groups was mapped before cycling. Flaw maps were made in the as-welded condition and at various load levels into the yielding range. The maps were obtained by using a rather coarse-grid monitoring approach. In the semiminor axis direction (a direction), a spacing of 0.1 cm (0.039 in.) between readings was used. Readings in the C-direction were taken at an interval of 0.25 cm (0.1 in.). By reading the ultrasonic amplitude using the pitch-catch technique (as previously described), the flaw boundary could be readily established.

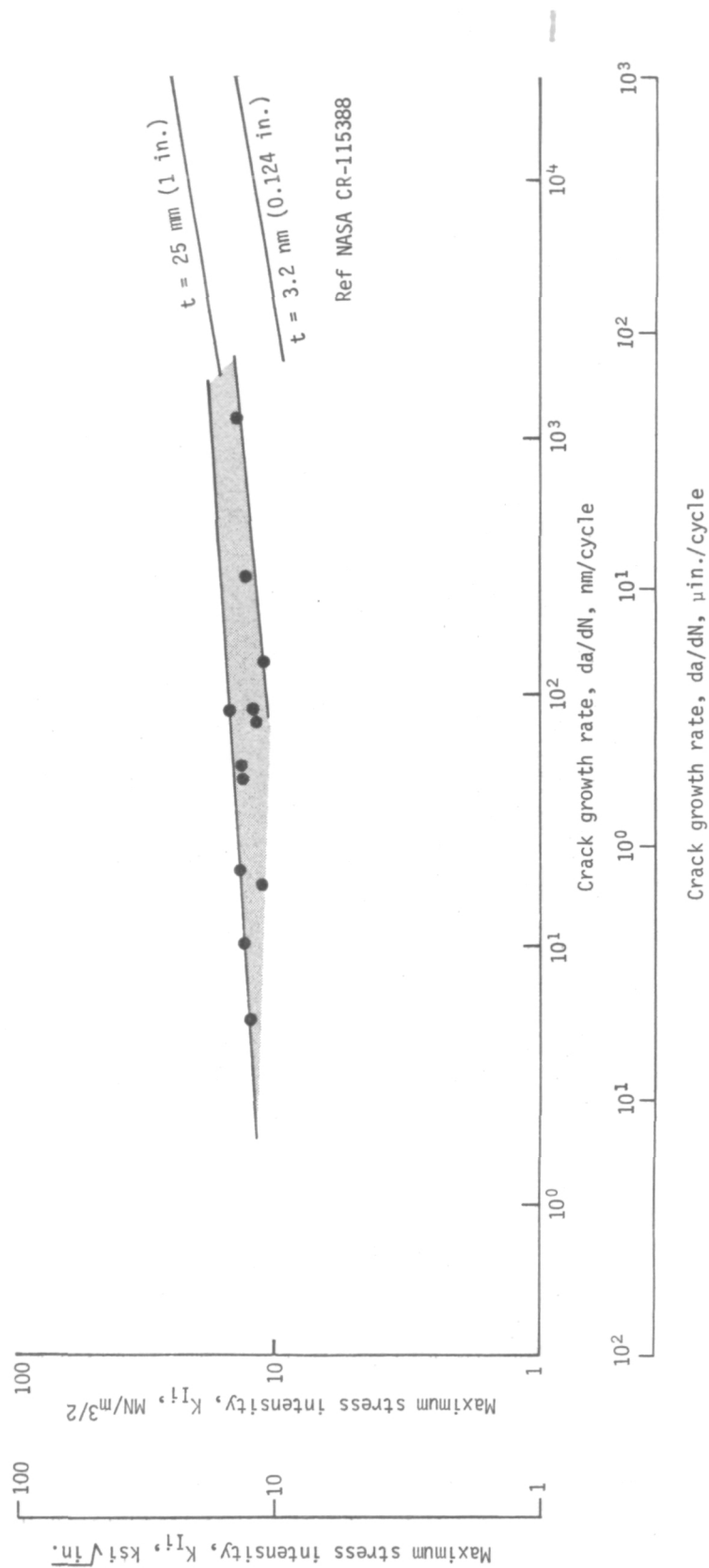


Figure 69. - Cyclic crack growth data for flat specimens.

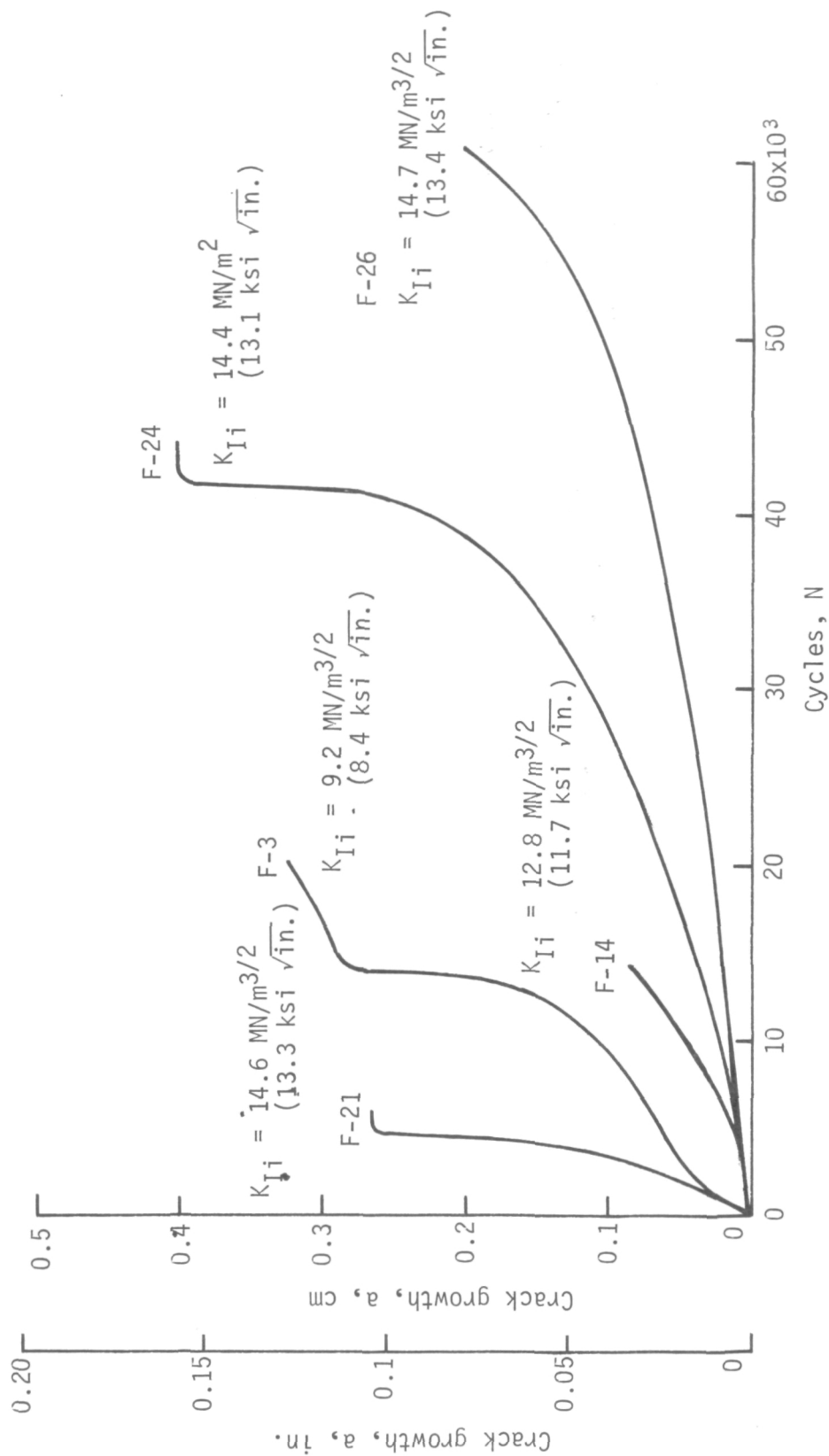


Figure 70. - Crack growth curves for flat specimens.

Specimen F-3 contained the smallest defect. Figure 71 is a flaw map and fractograph of the fracture face. The agreement between the map and actual contour is relatively poor--principally because of the coarse grid spacing used and the relatively large beamwidth diameter compared to the defect size. Beam width was approximately 0.25 cm (0.1 in.).

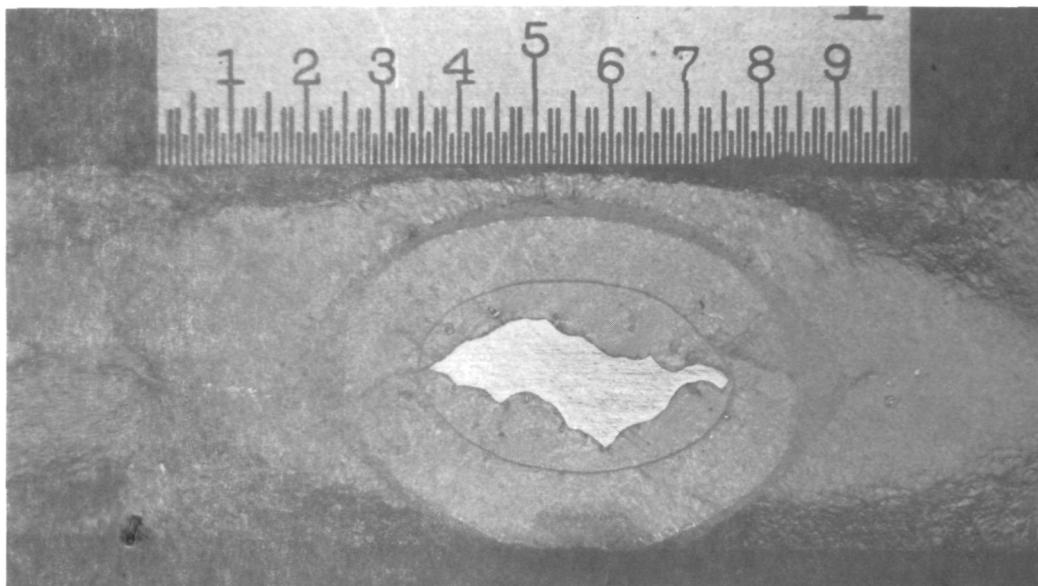
For the larger defect specimens, agreement between the flaw maps and actual appearances was much better. Figures 72, 73, 74 and 75 illustrate the results for the four larger defects (F-14, F-37, F-22, and F-47). Note the manner in which the defects opened. The smaller defects were completely closed at zero load, then began to open in one region and increase in detectible area with increasing load. A stress exceeding the yield strength was required to achieve full opening. The largest flaw exhibited small open areas at zero load at each end of the defect. Opening occurred by enlargement of each of these areas with increasing load. Flaw maps produced by incremental loading indicate the nature of the residual compressive forces resulting from welding that act on the lack-of-fusion defect. It is apparent that the highest forces act on the center part of the defect, with the ends relatively free of high compressive stresses.

Specimen F-3 was remapped after opening, using a grid spacing of 0.63 mm (0.025 in.) in the C direction. The data plot in figure 76 used that information and attempted to correct for beam width. The agreement between the map and actual defect shape was quite good. Although shape agreement was good, they do not appear to match well. It is possible that the map could be in error with respect to orientation of the free surface of the material. A small rotation of the map shows a much better agreement between the map and actual defect.

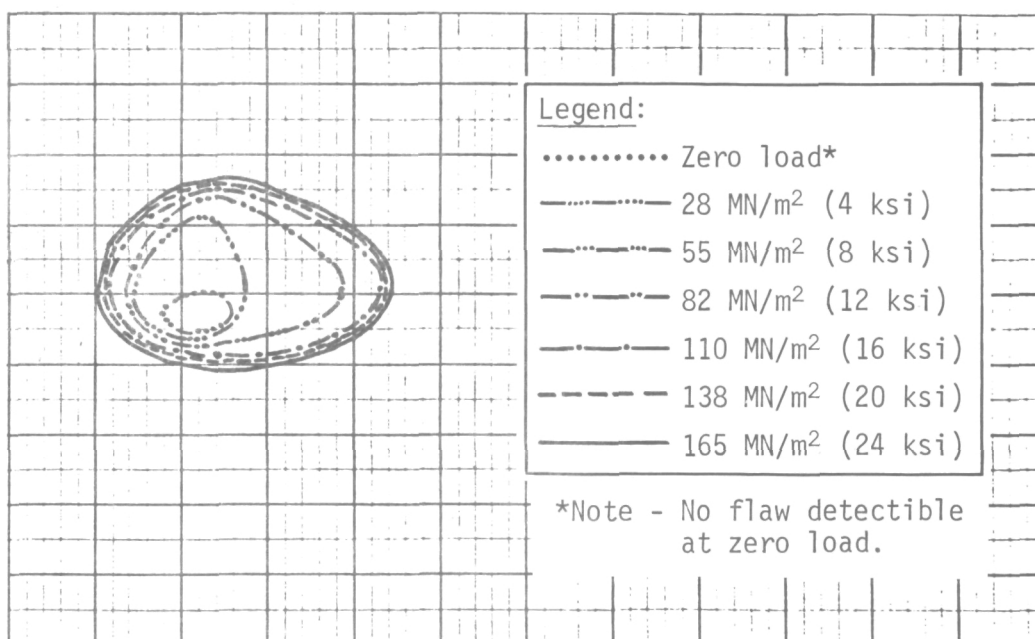
Specimen F-3 was cycled to grow the crack, then mapped. The coarse grid was used to produce the flaw map, and no beam width correction was used in data processing. As shown in figure 77, agreement between the map and defect is relatively poor.

Specimen F-15 was cycled until breakthrough to the surface was indicated. At this point, the flaw was mapped. Figure 78 shows the rather good agreement between flaw map and defect for this slightly larger defect.

Specimen F-22 was flaw mapped after cycling for 10 000 cycles at 124 MN/m^2 (18 ksi). Agreement between flaw map and actual defect size was quite good (fig. 79).



4X



4X

Figure 71. - Flaw map and fractograph for specimen F-3.

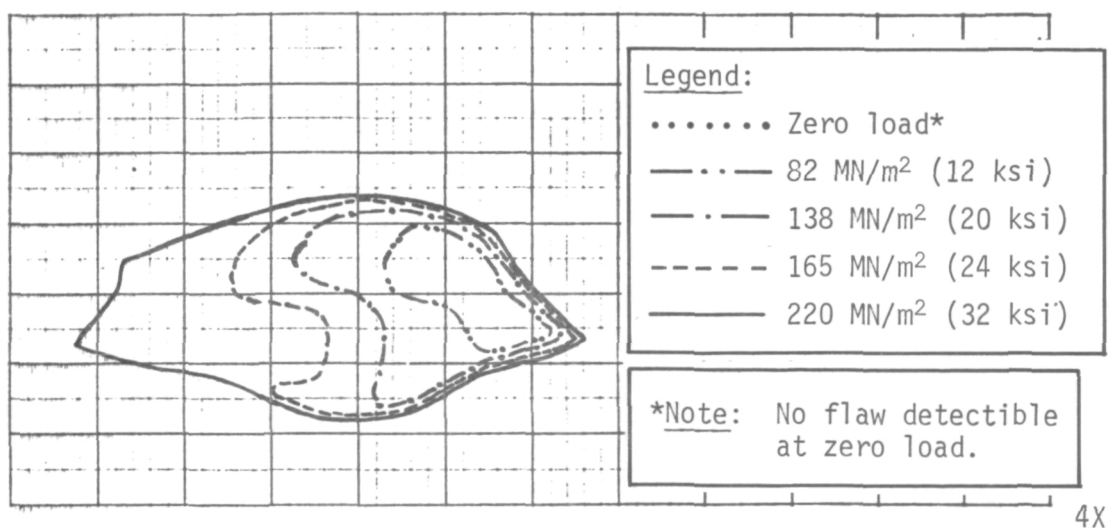
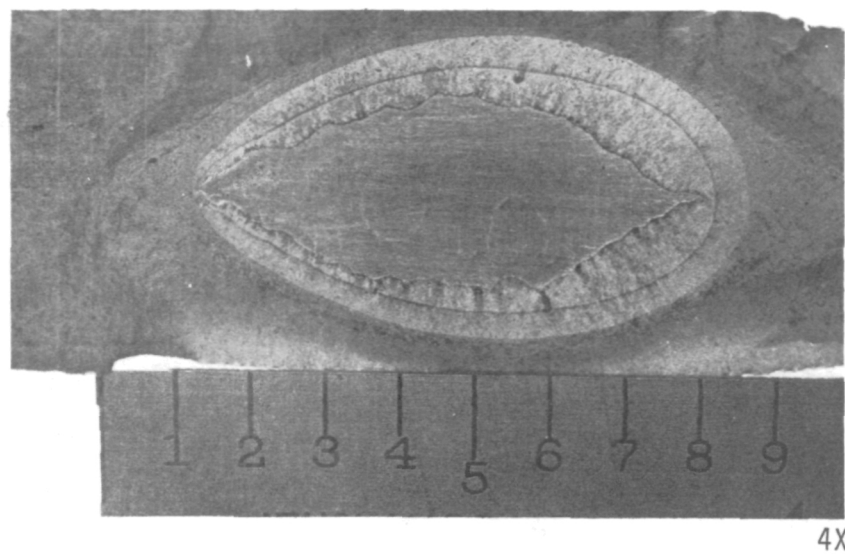
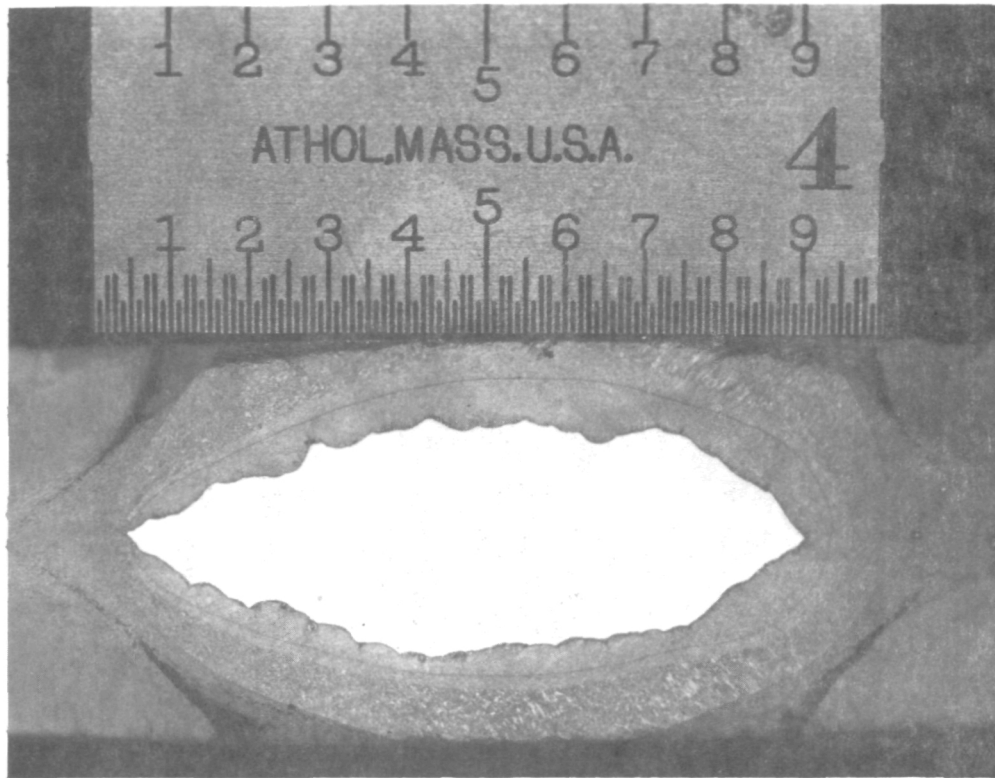
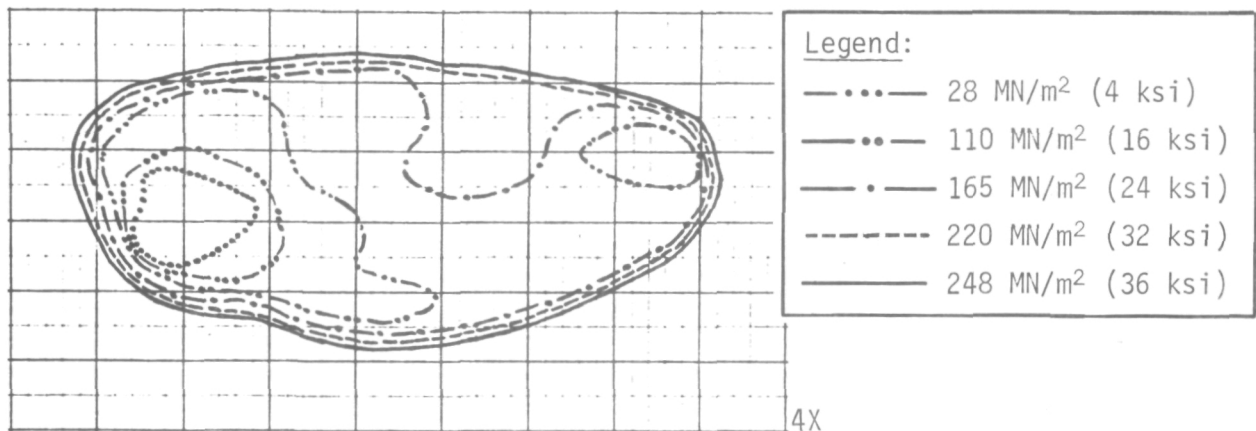


Figure 72. - Flaw map and fractograph for specimen F-14.



4X



4X

Figure 73. - Flaw map and fractograph for specimen F-22.

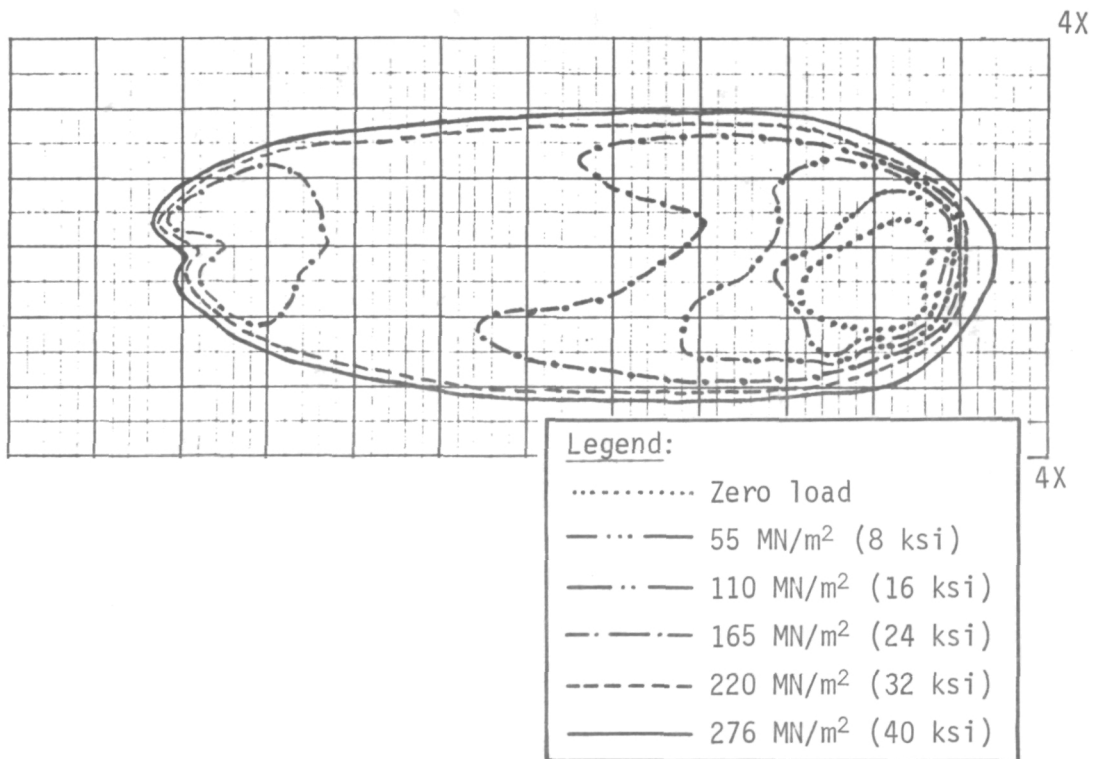
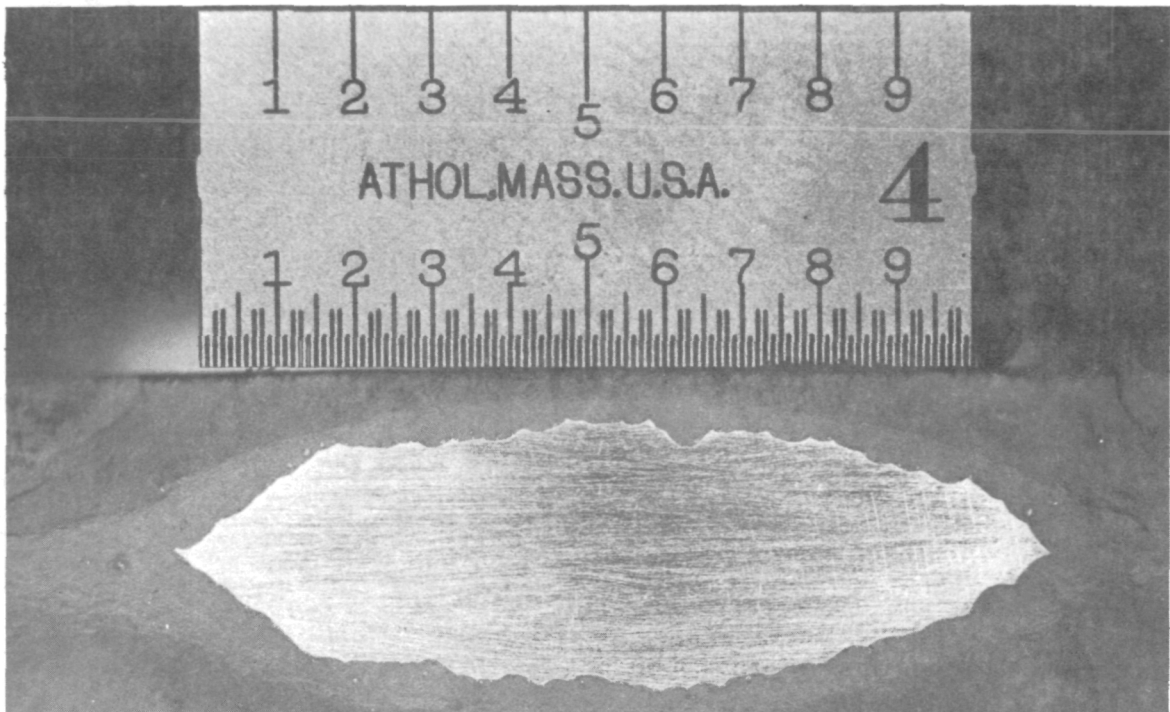
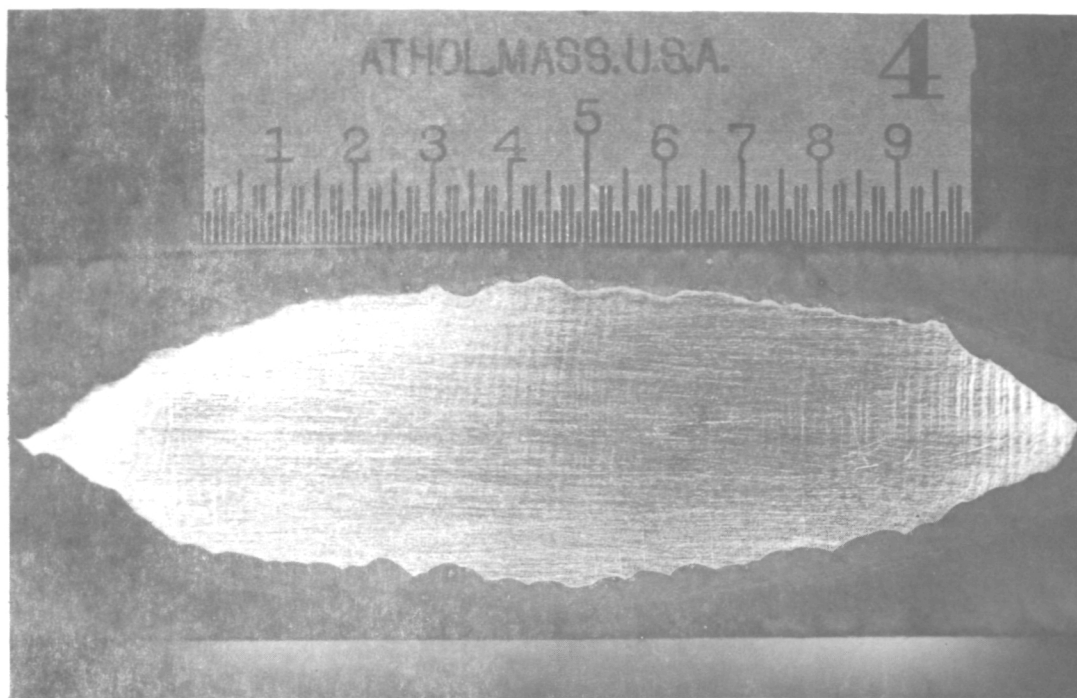
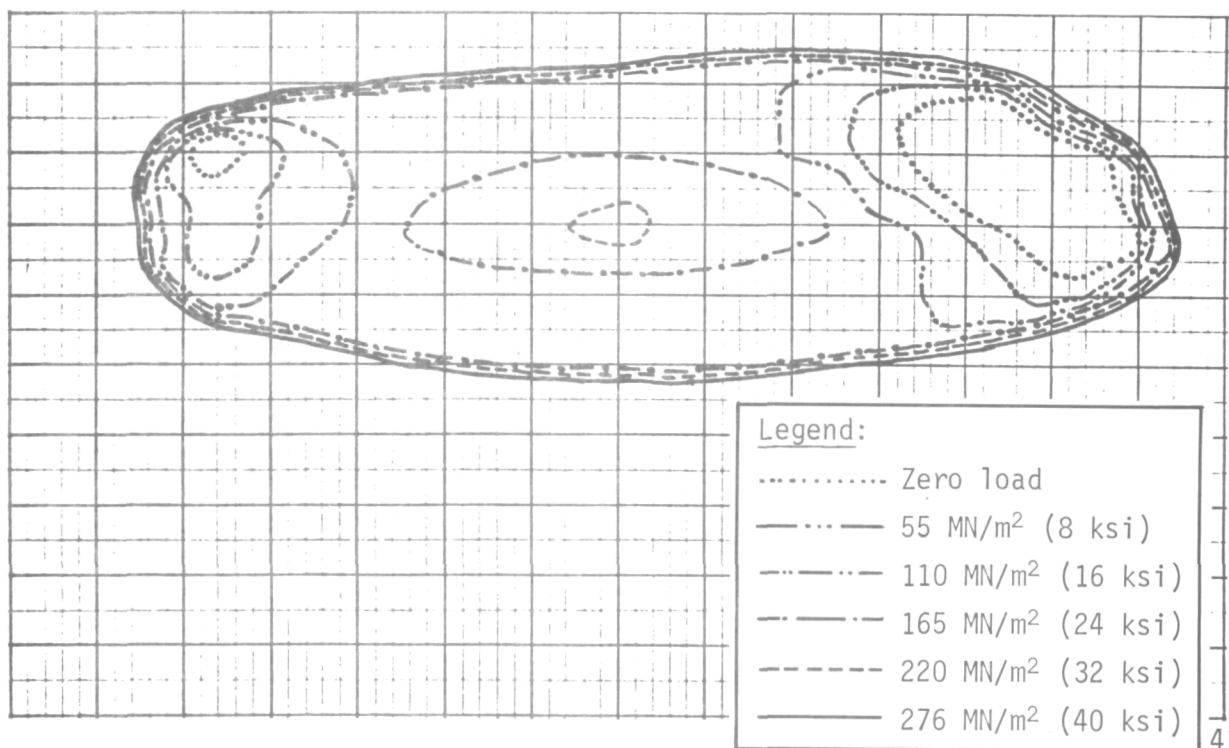


Figure 74. - Flaw map and fractograph for specimen F-37.



4X



4X

Figure 75. - Flaw map and fractograph for specimen F-47.

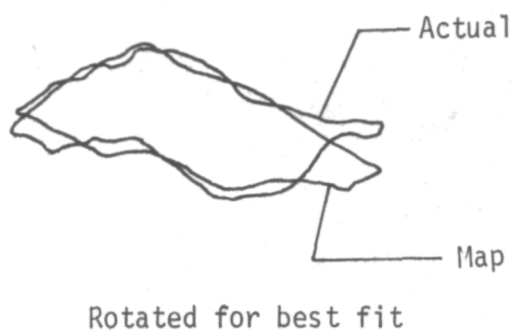
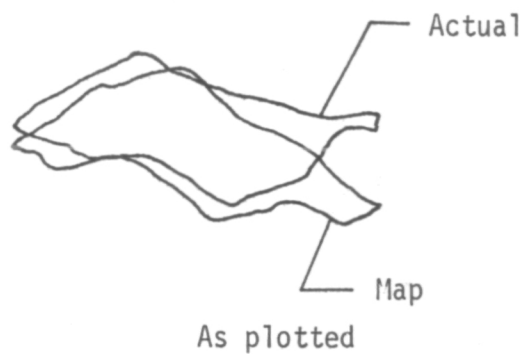


Figure 76. - Flaw map for specimen F-3 with finer grid spacing and beam width correction.

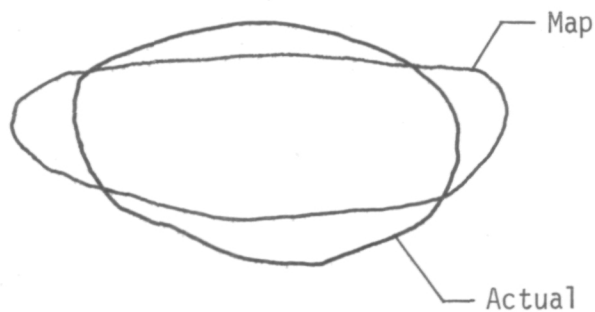


Figure 77. - Flaw map for specimen F-3 after cycling.

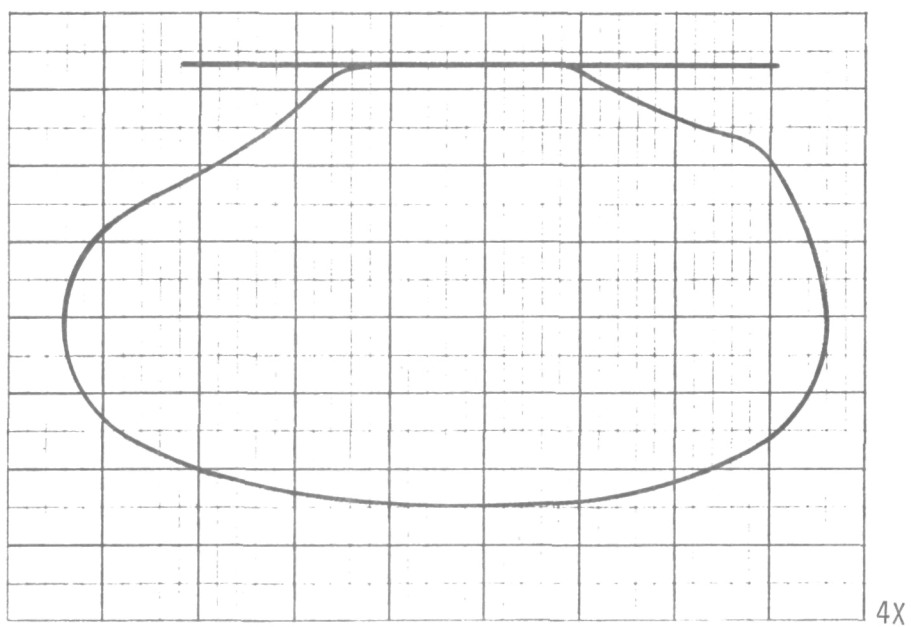
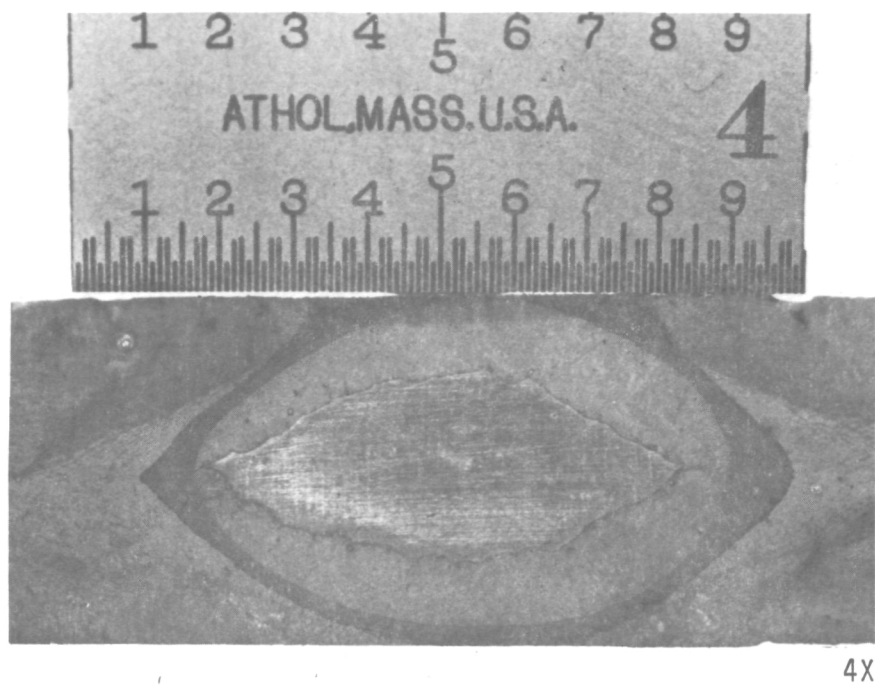


Figure 78. - Flaw map and fractograph for specimen F-15 after breakthrough.

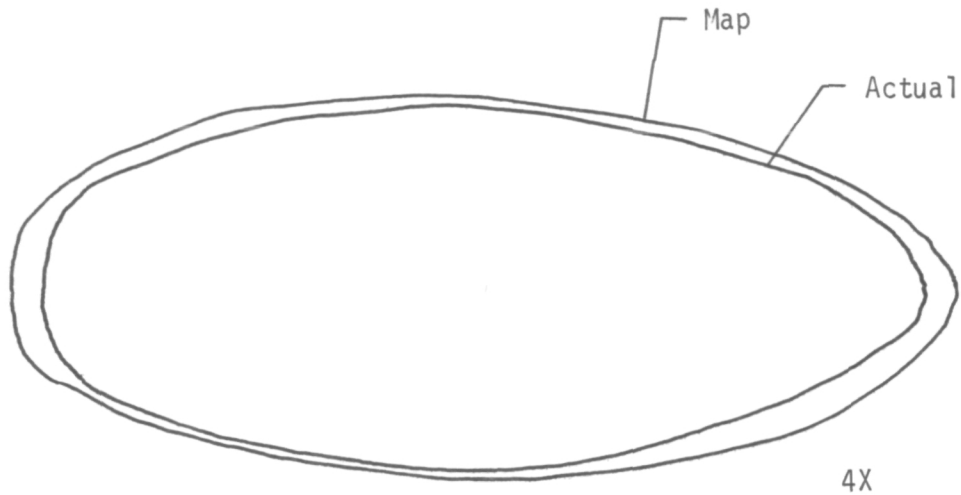


Figure 79. - Flaw map for specimen F-22 after cycling.

Specimen F-26 was cyclically loaded in increments until the defect penetrated the free surface. The specimen was flaw mapped each time the loading cycles were interrupted. Agreement between the flaw map and fracture face is particularly outstanding (fig. 80).

These results clearly show that the ultrasonic pitch-catch technique can be used to provide data on the size, shape, and location of defects. Furthermore, by taking measurement during load application, estimates of the tightness of defects can be established. The technique lends itself to flaw monitoring during cycling and to establishment of ligament penetration behavior.

Despite the fact that measurements were taken with a relatively coarse grid spacing and with an arbitrarily selected collimated beam width, the data are quite accurate. Optimization of the collimated beam and refinement of the traversing apparatus to provide for autographic recording would greatly enhance the fidelity of the resulting data.

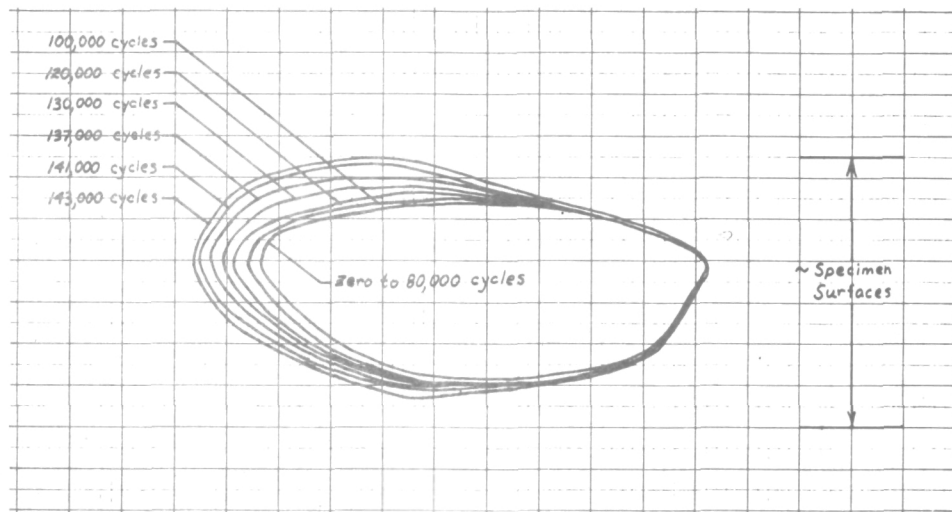
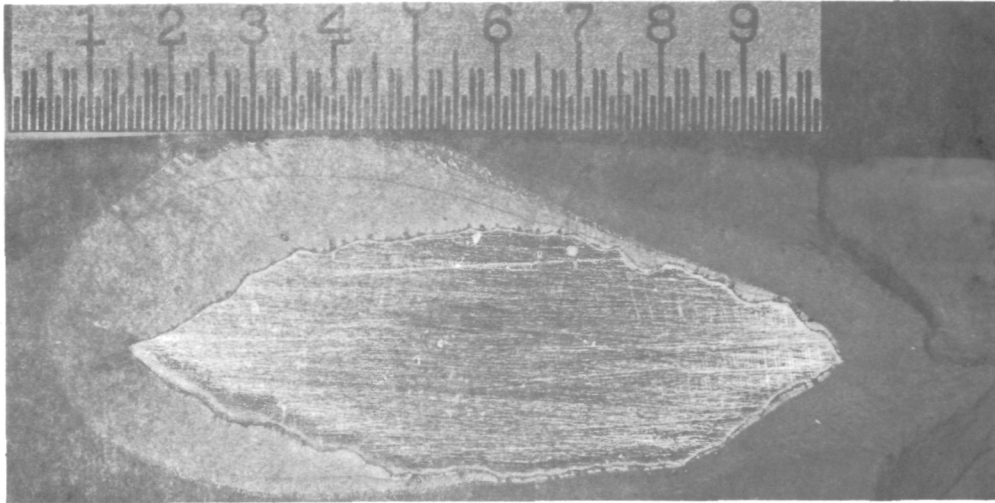


Figure 30. - Flaw map and fractograph of specimen F-25 after breakthrough.

CONCLUSIONS

This experimental investigation was undertaken to provide a rational basis for selection of proof test and nondestructive inspection (NDI) acceptance criteria for 2219 aluminum weldments. Because proof test alone cannot assure integrity for tough materials, NDI must be used as a companion for hardware qualification. Lack of a fusion defect is particularly difficult to detect and characterize in the as-welded condition. Therefore, proof testing must be used to ensure detectability of this type of defect.

Simulation of crack closure conditions that affect NDI detectability by compressing two blocks showed that forces well above the yield level were required to completely obscure the interface at ambient and elevated temperatures. This observation is in accord with other, more limited, investigations. The effect of surface roughness was apparent but of minor significance; the rougher surfaces required slightly greater force to obscure than a smooth surface.

Development of techniques for preparation of specimens containing artificially introduced lack-of-fusion weld defects was a significant accomplishment. Specimens were prepared with defects approximating the circular and elliptical shapes required for fracture-mechanics analyses. Test specimens were relatively free from the porosity that frequently rings artificially introduced defects. The welds produced contained tightly closed defects and were good simulations of those found in hardware.

As-produced defects were invisible to radiographic inspection and virtually indistinguishable using ultrasonic inspection. The force required to produce full opening of the defects was related to the tightness of the crack. Using the through-transmission technique, it was found that the opening force increased with decreasing initial ultrasonic signal strength. A low initial ultrasonic signal indicates a tight crack, because of compressive residual stresses. The force required to produce opening varied from approximately half the yield strength to well beyond yield. Because the geometries and techniques used to prepare the welded specimens produced significant variations in residual stresses, it became obvious that loading to overcome the effects of residual stress was required to produce opening. Cylindrical specimens were typified by low to moderate residual stresses; flat specimens, by virtue of fewer passes and low heat input, exhibited relatively high residual stresses. Ultrasonic inspection under controlled conditions appears to be a feasible method of estimating the magnitude of residual stress acting on a defect.

A method that combines a collimated ultrasonic beam and a pitch-catch technique was used to study the behavior of lack-of-

fusion defects in the flat welded specimens. This technique, developed under independent funding, basically uses an ultrasonic transmitter transducer to impress a signal in a material. The signal is then reflected from the far surface at a reflected angle equal to the incident angle and received by a carefully aligned second transducer. By collimating the beam, discontinuities in the material that interrupt the beam continuity can be accurately located by appropriately traversing the area of interest. Using this approach, the nature of crack opening during loading and cyclic flaw growth progression were determined and defect boundaries were mapped.

It was found that defect opening did not occur uniformly. Some portions of the defect opened well before other areas. For larger defects, opening first occurred near the ends of the major axis of the ellipse. These two regions increased in size with loading until they finally merged. Although stresses well above yield were required to produce full opening in these specimens, sufficient opening was found at or slightly below the yield strength to permit accurate characterization of defect geometry.

Flaw mapping and crack propagation studies showed that very high accuracy could be obtained for establishing a point on the crack front. Because of the use of relatively coarse grid spacings, actual maps produced were less accurate than the potential of the system.

Crack growth studies showed that rates for growth of buried defects were comparable to these of specimens containing artificial defects introduced by fatigue precracking after welding.

The ultrasonic pitch-catch system described in this report exhibits great promise in several ways. As a laboratory tool, it has potential for use in fracture mechanics studies of surface-flaw specimens for which measurements of flaw-front location, crack opening, and ligament thickness cannot be made by other means. Compliance measurements have been used in attempts to study interior crack behavior, but have not been generally satisfactory. Although development work is required, the ultrasonic system is promising for application to production welds.

Data generated clearly show that even tight weld defects exhibit sufficient opening at the levels used for proof testing to be considered inspectable using ultrasonic techniques. Before proof loading, these defects are difficult to detect and impossible to map. Program results illustrate the potential value of postproof inspection. Proof levels now used for 2219 aluminum pressure vessels are adequate to provide for enhancement of detectability.

Although the value of a postproof inspection is verified in terms of improved detectability of buried lack-of-fusion weld defects, it must be noted that the Space Shuttle External Tank being developed is not scheduled to use postproof inspection after qualification of initial hardware. For a single mission application, this approach is sound. Fracture mechanics studies of pre-cracked coupons representing External Tank conditions have shown that, if a defect that is in an incipient penetration or fracture condition survives proof loading, it can also survive four mission cycles at stresses in the vicinity of the proof level (ref. 3). For vessels requiring long life, application of a postproof inspection is necessary.

The observation that some degree of residual opening of tight cracks occurs at stresses below proof levels provides the basis for an alternative approach to proof testing that might be considered for future applications. As we have seen, buried defects in the as-welded condition are difficult to detect. Postproof inspection enhances detectability, but there is a risk of proof failure. An alternative approach is to prestress at a level sufficiently below the proof level to avoid catastrophic failure, but sufficiently high to provide inspection enhancement. This approach is based on developing data for the particular weld thicknesses involved to permit assessment of the leak-versus-fracture boundary as a function of defect size, then attempting to predict the maximum size that could be present in the structure. By so limiting the mode of failure to leak rather than fracture, the loss risk is decreased and inspectability is increased.

This program has provided data that help to develop a better understanding of the requirements for proof testing and NDI of aluminum pressure vessels. In summary, the following conclusions can be drawn:

- 1) lack-of-fusion weld defects are sufficiently tight in the as-welded condition to be considered undetectable;
- 2) proof-level loads are required to fully open lack-of-fusion weld defects;
- 3) significant crack opening occurs at subproof levels so that an inspection enhancement loading treatment designed to avoid catastrophic failure is feasible;
- 4) currently used proof levels for 2219 pressure vessels are adequate for postproof inspection;
- 5) quantification of defect size and location using collimated ultrasonic pitch-catch techniques appears sufficiently feasible for tankage to warrant developmental work;

- 6) for short-time, single-cycle pressure-vessel applications, postproof inspection is desirable;
- 7) for long-term multiple-cycle pressure-vessel applications, postproof inspection is essential for life assurance.

REFERENCES

1. Martin, B. G. and Adams, D. J.: *Detection of Lack-of-Fusion in Aluminum Alloy Weldments by Ultrasonic Shear Waves*, Douglas Missile and Space Systems Division Paper No. 3499,
2. The Boeing Company: *Determination of Design Allowable Properties - Fracture of 2219-T87 Aluminum Alloy*, NASA CR-115388, March 1972.
3. Martin Marietta Corporation: *Fracture Mechanics Data on 2219-T87 Aluminum for the Space Shuttle External Tank*, Test Report 826-2027, July 1975.

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